PB81-151557

Processing Equipment for Resource Recovery Systems. Volume III Field Test Evaluation of Shredders

Cal Recovery Systems, Inc.
Richmond, CA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Jul 80

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-80-007c
July 1980

Research and Development

PB81-151557

EPA

Processing Equipment for Resource Recovery Systems

Vol. III
Field Test Evaluation of Shredders

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-80-007c	2.	3. RECIPIENT'S ACCESSION NO. PB81 151557
4. TITLE AND SUBTITLE PROCESSING EQUIPMENT FOR RESOURCE RECOVERY SYSTEMS Volume III. Field Test Evaluation of Shredders		5. REPORT DATE July 1980 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) George M. Savage and Geoffrey R. Shiflett		8. PERFORMING ORGANIZATION REPORT NO. 4426-D (Project Number)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Cal Recovery Systems, Inc.* 160 Broadway, Suite 200 Richmond, California 94804		10. PROGRAM ELEMENT NO. 1NE624E624DWF COS Wastes as Fuels Task 5.1 11. CONTRACT/GRANT NO. Contract No. 68-03-2589
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final Report - Vol. III of III 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES Project Officer: Donald A. Oberacker 513/684-7881
*Conducted under subcontract with Midwest Research Institute, Kansas City, Missouri
See also Volume I (EPA-600/2-80-007a) and Volume II (EPA-600/2-80-007b)

16. ABSTRACT

This report presents the results of a program to test and evaluate large-scale shredders used for the size reduction of solid waste. In all, tests were conducted on seven horizontal hammermills, one vertical hammermill, and one vertical ring shredder at six commercial sites (Appleton, Wisconsin; Ames, Iowa; Cockeysville, Maryland; Great Falls, Montana; Tinton Falls, New Jersey; and Odessa, Texas). Both two stage size reduction (Ames) and single stage size reduction were studied as part of this work. Evaluation and interpretation of the data have resulted in the development of analytical relationships among the comminution parameters and the establishment of levels of performance with respect to energy consumption and hammer wear associated with size reduction of solid waste.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Shredders Solid waste Size reduction Hammermill Energy Wear	Research Refuse disposal	Solid waste Waste as Energy	13B 68

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* unclassified	21. NO. OF PAGES 137
	20. SECURITY CLASS *(This page)* unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980--657-165/0038

EPA-600/2-80-007c
July 1980

PROCESSING EQUIPMENT FOR RESOURCE RECOVERY SYSTEMS

Volume III. Field Test Evaluation of Shredders

by

George M. Savage
Geoffrey R. Shiflett
Cal Recovery Systems, Inc.
Richmond, California 94804

Contract No. 68-03-2589

Project Officer

Donald A. Oberacker
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is a necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory developes new and improved systems technology to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research.

This report presents the results of a study of nine shredders used for size reduction of municipal solid wastes in six processing plants. This is the third in a series of reports on studies of processing equipment for resource recovery systems. Volume I - State of the Art including research needs, and Volume II - Magnetic Separators, Air Classifier and Ambient Air Emissions Tests were prepared under EPA Contract No. 68-03-2387. Volume III - Field Evaluation of Shredders, was conducted under EPA Contract No. 68-03-2589.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This report presents the results of a program to test and evaluate large-scale shredders used for the size reduction of solid waste. In all, tests were conducted on seven horizontal hammermills, one vertical hammermill, and one vertical ring shredder at six commercial sites (Appleton, Wisconsin; Ames, Iowa; Cockeysville, Maryland; Great Falls, Montana; Tingon Falls, New Jersey; and Odessa, Texas). Both two stage size reduction (Ames) and single stage size reduction were studied as part of this work. Evaluation and interpretation of the data has resulted in the development of analytical relationships among the comminution parameters and the establishment of levels of performance with respect to energy consumption and hammer wear associated with size reduction of solid waste.

This report was submitted in fulfillment of Contract No. 68-03-2589 by Midwest Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from September 1, 1977 to February 28, 1979.

CONTENTS

Foreword iii
Abstract iv
Figures. vii
Tables x
Definitions and Nomenclature xii
Acknowledgment xiv

1. Introduction. 1
    Overview 1
    Site descriptions. 2
    Hammer maintenance programs. 26
2. Findings and Conclusions. 33
    Energy and Particle Size 34
    Hammer wear. 36
3. Recommendations 37
4. Materials and Methods .39
    Power monitoring instrumentation 39
    Other equipment. 42
    Size distribution analysis 43
5. Experimental Procedures 44
    General procedures for power-flow rate data collection . . .44
    Appleton procedure 46
    Ames procedure 47
    Cockeysville procedure 49
    Great Falls procedure. 50
    Tinton Falls procedure 51
    Odessa procedure 52
    Hammer wear experimental procedure 53
6. Results and Discussion. 59
    Moisture content of shredded refuse. 59
    Measured throughputs .59
    Size distribution of shredded solid waste. 61
    Measured power 64
    Throughput effects on size 64
    Estimation of specific energy requirements 69
    Motor sizing 72

CONTENTS (continued)

6. Results and Discussion (continued). 59
- Power-flow rate-moisture relationships 72
- Discussion of Appleton holdup data 78
- Discussion of the results for the Ames primary and secondary shredders. 79
- Discussion of bi-directional rotation of Cockeysville #1 shredder 80
- Discussion of Great Falls vertical hammermill results. 81
- Discussion of Tinton Falls vertical ring shredder results. 83
- Comparison of Cockeysville and Odessa results. . . . 83
- Specific energy comparison of single versus multiple stage size reduction of MSW 85
- Results of hammer wear studies 89
- Comparison of hammer wear data among sites 96
- Site specific comments with regard to hammer maintenance. 99
- Summary of shredder performance. 99

7. Costs Associated with Refuse Size Reduction 100
- Energy costs for shredding 100
- Comparison of alternative hammer maintenance programs 100
- Summary of costs 104

References 105
Appendix 106

FIGURES

Number Page

1 Outagamie County Solid Waste Plant; Appleton, Wisconsin 4

2 West mill at the Appleton site 5

3 View of west mill and motor 5

4 Flow schematic for Appleton facility 7

5 Solid waste recovery system; Ames, Iowa 8

6 Ames primary shredder shown partially disassembled 9

7 Flow schematic for Ames plant 11

8 Baltimore County Resource Recovery Facility; Cockeysville, Maryland 13

9 Shredder #1 at Cockeysville 14

10 Flow schematic of Cockeysville plant 16

11 Great Falls Solid Waste Reduction Facility; Great Falls, Montana 16

12 Exterior view of Great Falls vertical hammermill 18

13 Interior view of Great Falls vertical hammermill 18

14 Flow schematic of Great Falls facility 19

15 Monmouth County Reclamation Center; Tinton Falls, New Jersey 20

16 Interior of Monmouth County Reclamation Center, Plant 2 22

17 Interior of vertical ring shredder 22

18 Flow schematic of Tinton Falls facility 23

19 City of Odessa Solid Waste Management Facility; Odessa, Texas 24

20 Odessa horizontal hammermill 25

FIGURES (continued)

Number Page

21 Flow schematic of Odessa facility 28

22 Hammers undergoing hardfacing at Appleton; weld deposite are shown on hammer tips 29

23 Hardfacing application at the Cockeysville facility 29

24 Utilization of pin puller for hammer changes 30

25 View of hammers in Ames primary shredder 30

26 Inside view of Ames secondary shredder 31

27 New hammer for Ames secondary shredder 31

28 Worn hammers from Ames secondary shredder 32

29 Used and new ring grinders for Tinton Falls vertical shredder 32

30 Power monitoring equipment; Appleton 40

31 Installation of voltage and current transformers; Appleton .. 40

32 Schematic layout of power monitoring equipment 41

33 Cleaned hammer being weighed prior to installation in west mill 55

34 Set of newly hardfaced hammers ready for installation at the Cockeysville facility 55

35 Pictoral of vertical hammermill 56

36 Internal configuration of the Tinton Falls ring shredder 58

37 Relationship between nominal and characteristic product sizes for shredded MSW 62

38 Range of size distributions of shredded MSW measured at Appleton, Ames, and Cockeysville 63

39 Average size distribution of raw and shredded solid waste ... 64

40 Relationship of product size and throughput for Ames primary shredder 67

41 Relationship of product size and throughput for Ames secondary shredder 67

FIGURES (continued)

Number Page

42 Relationship of product size and throughput for Tinton Falls shredder 68

43 Relationship of product size and throughput for Odessa shredder 68

44 Specific energy consumption (A.D.B.) as a function of product size 69

45 Specific energy consumption (W.B.) as a function of product size 71

46 Net power draw of Appleton East Mill 73

47 Net power draw of Ames primary shredder 74

48 Net power draw of Ames secondary shredder 74

49 Net power draw of Cockeysville #1 shredder 75

50 Net power draw of Great Falls 20 TPH shredder 75

51 Net power draw of Tinton Falls shredder 76

52 Net power draw of Odessa shredder 76

53 Cross-sectional view of discharge under #1 shredder at Cockeysville 81

54 Relationship between flow rate and specific energy for Great Falls vertical hammermill 82

55 Representative hammermill and ring grinder power recordings . 84

56 Comparison between Odessa and Cockeysville flow rate-size relationships 86

57 Hammer wear as a function of allow hardness 90

58 Hammers removed from Great Falls vertical hammermill 93

59 Hammer installation pattern for Great Falls wear experiments 95

60 Hammer wear as a function of alloy hardness and degree of size reduction 98

61 Cost of energy associated with size reduction 101

TABLES

Number		Page
1	Summary of Tests Conducted for the Shredder Evaluation Studies	3
2	Appleton Shredder Specifications	6
3	Ames Shredder Specifications	10
4	Cockeysville Shredder Specifications	15
5	Great Falls Shredder Specifications	17
6	Tinton Falls Shredder Specifications	21
7	Odessa Shredder Specifications	27
8	Transformer Ratios Used at Each Site	42
9	Sample Size	46
10	Summary of Average Values of Important Parameters Measured During the Shredder Performance Evaluation	60
11	Throughputs Measured During Shredder Performance Evaluations	61
12	Power Measured During Shredder Performance Evaluations	65
13	Effect of Variation of Throughput Upon Characteristic Product Size and Specific Energy	66
14	Specific Energy Requirements Versus Product Size Utilizing Test Results from Vertical and Horizontal Hammermills	72
15	Results of Multiple Regression Analyses; Net Power as a Function of Flow Rate and Moisture Content	77
16	Shredding Data Used to Develop Comparisons Between Single and Multiple Stage Size Reduction	87
17	Net Power and Energy Requirements for Single and Multiple Stage Size Reduction	88

TABLES (continued)

Number Page

18 Calculation of Required Gross Specific Energy to Obtain Equivalent Product Size for Ames and Cockeysville 88

19 Appleton Hammer Wear Experiments 90

20 Ames Hammer Wear Experiments 91

21 Cockeysville Hammer Wear Experiments 92

22 Great Falls Hammer Wear Experiments 94

23 Odessa Hammer Wear Experiments 94

24 Tinton Falls Wear Experiments 95

25 Normalization of Hammer Wear Measurements 98

26 Typical Costs for Hammer Maintenance 102

27 Cost Summary for Hammer Maintenance Programs 103

DEFINITIONS AND NOMENCLATURE

DEFINITIONS

Characteristic Size	Screen size corresponding to 63.2% cumulative weight percent passing
Degree of Size Reduction (Z_o)	Defined by the ratio $(F_o-X_o)/F_o$. A dimensionless parameter used to describe the amount of size reduction occuring during shredding, e.g. $Z_o = 0$ implies no size reduction, $Z_o = 0.90$ imnlies characteristic product size, X_o, is equal to 0.10 F_o
Nominal Size	Screen size corresponding to 90.0% cumulative weight percent passing
Shredder Holdup	Material in shredder at any instant in time
Specific Energy	Net energy requirement (or consumption) expressed on the basis of net energy utilized per ton of waste shredded
Tons	In all cases, the word tons refers to metric tons (1000 kilograms)

ABBREVIATIONS

A.D.B.	Air dry weight basis
Kwh	Kilowatt hour
Kwh/T	Kilowatt-hours per ton
MC	Air dry moisture content
R_c	Rockwell "C" hardness scale
T_d	Metric tons on an air dry weight basis
TPH	Metric tons per hour
TPY	Metric tons per year
T_w	Metric tons on a wet weight basis
W.B.	Wet weight basis

DEFINITIONS AND NOMENCLATURE (continued)

VARIABLES AND PARAMETERS

E_o	Specific energy consumption on an air dry weight basis
$\overline{E}_o$	Average specific energy consumption on an air dry weight basis
E_{o_w}	Specific energy consumption on a wet weight basis
$\overline{E}_{o_w}$	Average specific energy consumption on a wet weight basis
F_o	Characteristic feed size
H	Shredder holdup
$\dot{m}_d$	Flow rate (throughput) on an air dry weight basis
$\dot{m}_w$	Flow rate (throughput) on a wet basis
P_{FW}	Freewheeling power
P_G	Gross power
P_N	Net power ($P_N = P_G - P_{FW}$)
w_i	Average material weight loss per hammer per ton of waste shredded
W_o	Hammer wear of a full complement of hammers on the basis of material loss per ton of waste shredded
X_o	Characteristic product size (screen size corresponding to 63.2% cumulative passing)
$\overline{X}_o$	Average characteristic product size
X_{90}	Nominal size (screen size corresponding to 90% cumulative passing)
$\overline{X}_{90}$	Average nominal product size
Z_o	Degree of size reduction, $(F_o - X_o)/F_o$
σ_{E_o}	Standard deviation of specific energy on an air dry weight basis
$\sigma_{E_{o_w}}$	Standard deviation of specific energy on a wet weight basis
σ_o	Standard deviation of charactertistic product size
σ_{90}	Standard deviation of nominal product size

ACKNOWLEDGMENTS

The study of shredder operation and performance reported herein, was developed and conducted by Cal Recovery Systems, Inc. (CRS), Richmond, California, under Subcontracts No. 4424-D and 4426-D with Midwest Research Institute (MRI). The principals of CRS have been actively involved in the area of size reduction of solid waste for a period of 8 years. Their efforts in this field include pioneering work in the characterization of parameters governing the process of size reduction, development of analytical relationships governing size reduction of solid waste, and the influence of machine characteristics, such as rotor rpm and grate opening size upon product size, energy consumption, and hammer wear.

This study was conducted by Cal Recovery Systems under the direction of Dr. Louis F. Diaz and Mr. George M. Savage. Actual site testing and data analysis were performed by Mr. George M. Savage, Dr. Geoffrey R. Shiflett, and Mr. Stanley M. Boghosian. Mr. Savage and Dr. Shiflett are the principal authors of this report. The manuscript was typed and edited by Ms. Linda Eggerth.

The Project Director for MRI was David Bendersky, Principal Engineer. The EPA Project Officer was Donald A. Oberacker, Senior Mechanical Engineer.

The success of the testing programs at the six sites was to a large degree the consequence of the excellent cooperation shown to us by those associated with the shredding facilities. The cooperation of the following people was instrumental in arranging for testing at each site:

Mr. Robert Brickner, Allis Chalmers, Appleton, Wisconsin;
Mr. Eugene Higgins, Outagamie County, Appleton, Wisconsin;
Mr. Arnold Chantland, City of Ames, Iowa;
Mr. Hal Gordy, Teledyne National, Northridge, California;
Mr. Carl Able, City of Great Falls, Montana;
Mr. John Gray, Monmouth County, New Jersey; and
Mr. Dwayne Dobbs, City of Odessa, Texas.

In particular we wish to acknowledge the help and cooperation of the personnel from each plant, especially that of the plant managers, Mr. Ed Maloney (Appleton), Mr. Jerry Temple (Ames), Mr. Ken Cramer (Cockeysville), Mr. Dale Young (Great Falls), Mr. John Gray (Monmouth County), and Mr. Dwayne Dobbs (Odessa).

SECTION 1

INTRODUCTION

OVERVIEW

Over the past fifteen years, the use of shredders in the field of solid waste management has seen steady growth. From first attempts at using size reduction of solid waste as the initial step in the production of a suitable material for composting, the use of shredders has grown into the field of full-scale, integrated resource recovery facilities. In between these events, shredders have seen service in the areas of ferrous scrap recovery from solid waste and treatment of refuse for landfill disposal without the necessity of cover material.

Shredding (or synonymously, grinding, milling, size reduction, or comminution) of solid waste has taken on an added degree of significance since the emergence of large, full-scale resource recovery operations. For such facilities, size reduction often represents the first step in processing the waste stream. Consequently, the unit process of size reduction affects all equipment involved in downstream material handling and separation. In addition, the shredding operation normally accommodates 100 percent of the waste, whereas other unit processes in resource recovery plants generally handle only particular fractions of the waste stream. As a result, the importance of size reduction is generally recognized, albeit poorly understood, by the solid waste industry.

The proliferation of shredders in the solid waste industry has stimulated interest in their operation, evaluation, and performance. For example, criteria for estimating shredder operation and performance are needed in the design stage of resource recovery plants. Also, a plant manager may wish to know how certain operational changes involving a shredder (such as a change in size of the grate openings or variation in shredder throughput) may affect shredder operation (e.g. energy requirements and size of product).

Until now, only pilot-scale research data has been available for characterizing size reduction of solid waste. In fact, in-depth testing and evaluation of shredders has only been conducted on units with a capacity of less than 15 tons per hour. Consequently, the obvious question remains as to the usefulness of the results obtained from pilot-scale shredders when applied to the large-scale shredding operations of typical plants (in the range of 15 to 100 tons per hour).

The testing and evaluation program described in this report was initiated to extend the knowledge of solid waste size reduction and resolve the question concerning the applicability of pilot-scale research results.

The underlying motivation was to establish predictive relationships, design criteria, evaluation techniques, and levels of performance for large-scale size reduction equipment. The information contained herein has been developed for the use and consideration of those associated with solid waste management including shredder manufacturers, plant designers, plant operators, and researchers.

The test program involved detailed measurements of energy and hammer wear associated with size reduction of solid waste, the two most important aspects of size reduction due to their effects on operational cost. In order to ascertain relationships involving energy and hammer wear, a rigid, scientific protocol was established and implemented. Cooperation of personnel at each site was instrumental in maintaining a consistent test procedure among plants.

The test plans were directed toward assessment of energy consumption and hammer wear associated with shredding. In order to adequately assess energy consumption, the test program called for collection of samples to determine the product size and moisture content of shredded refuse. The samples were then correlated with energy consumption. The study concentrated on the evaluation of various hardfacing alloys as well as the base material typically used at each site for determination of hammer wear. Rates of hammer wear were determined and interpreted.

The shredders that were tested are installed at facilities located in Appleton, Wisconsin; Ames, Iowa; Cockeysville, Maryland; Great Falls, Montana; Tinton Falls, New Jersey; and Odessa, Texas.

Since the number and types of tests performed on the shredders at each site were necessarily site specific, Table 1 has been prepared to summarize the tests that were performed. In all, tests (either power or wear measurements) were conducted on nine shredders. Due to restraints present at some sites, both power and wear measurements could not be collected for some shredders, as shown in Table 1.

In order to acquaint the reader with the plants that were visited, the utilization of each shredder, the general processing sequence, and programs of hammer maintenance, the following two sections, Site Descriptions and Hammer Maintenance Programs, give a brief overview of each facility.

SITE DESCRIPTIONS

Appleton

The Outagamie County Solid Waste Shredding Facility (Figure 1) located in Appleton, Wisconsin, operates two Allis-Chalmers Model KH 12/18 horizontal hammermills (Figures 2 and 3) in parallel to shred the approximately 160 tons of refuse received daily. Ferrous material is recovered after shredding using a magnetic belt conveyor, and the remaining shredded waste is compacted into transfer trailers and transported to the landfill. Table 2 provides a summary of the principal features of the Appleton shredders, and a flow schematic for the Appleton facility is presented in Figure 4.

TABLE 1. SUMMARY OF TESTS CONDUCTED FOR THE SHREDDER EVALUATION STUDIES

Site	Type of Shredder[d]	Shredder Manufacturer	Average Throughput (T_WPH)	MEASUREMENTS		
				Energy Consumption	Particle Size	Hammer Wear
1. Appleton, Wi.						
East Mill	HSH	Allis Chalmers	24.8	(11)[b]	(11)[b]	(1)[c]
West Mill	HSH	Allis Chalmers	18.1	(3)	(3)[e]	(1)
2. Ames, Iowa						
Primary	HSH	American Pulverizer	18.6	(10)	(10)	(1)
Secondary	HSH	American Pulverizer	22.4	(10)	(10)	(0)
3. Cockeysville, Md.						
Shredder #1	HSH	Tracor-Marksman	49.5	(12)	(12)	(1)
Shredder #2	HSH	Tracor-Marksman	N.D.[a]	(0)	(0)	(1)
4. Great Falls, Mt						
20 TPH Mill	VSH	Heil	14.8	(12)	(12)	(1)
5. Tinton Falls, NJ						
Shredder #2	VRS	Carborundum	60.8	(12)	(12)	(1)
6. Odessa, Tx	HSH	Newell	82.0	(12)	(12)	(1)

Notes:

[a] Not determined

[b] Figures in this column refer to the number of tests conducted on each shredder

[c] Figures in this column refer to the number of data sets collected for hammer wear

[d] HSH = horizontal swing hammermill
VSH = vertical swing hammermill
VRS = vertical ring shredder

[e] This test data was used solely in conjunction with the hammer wear data

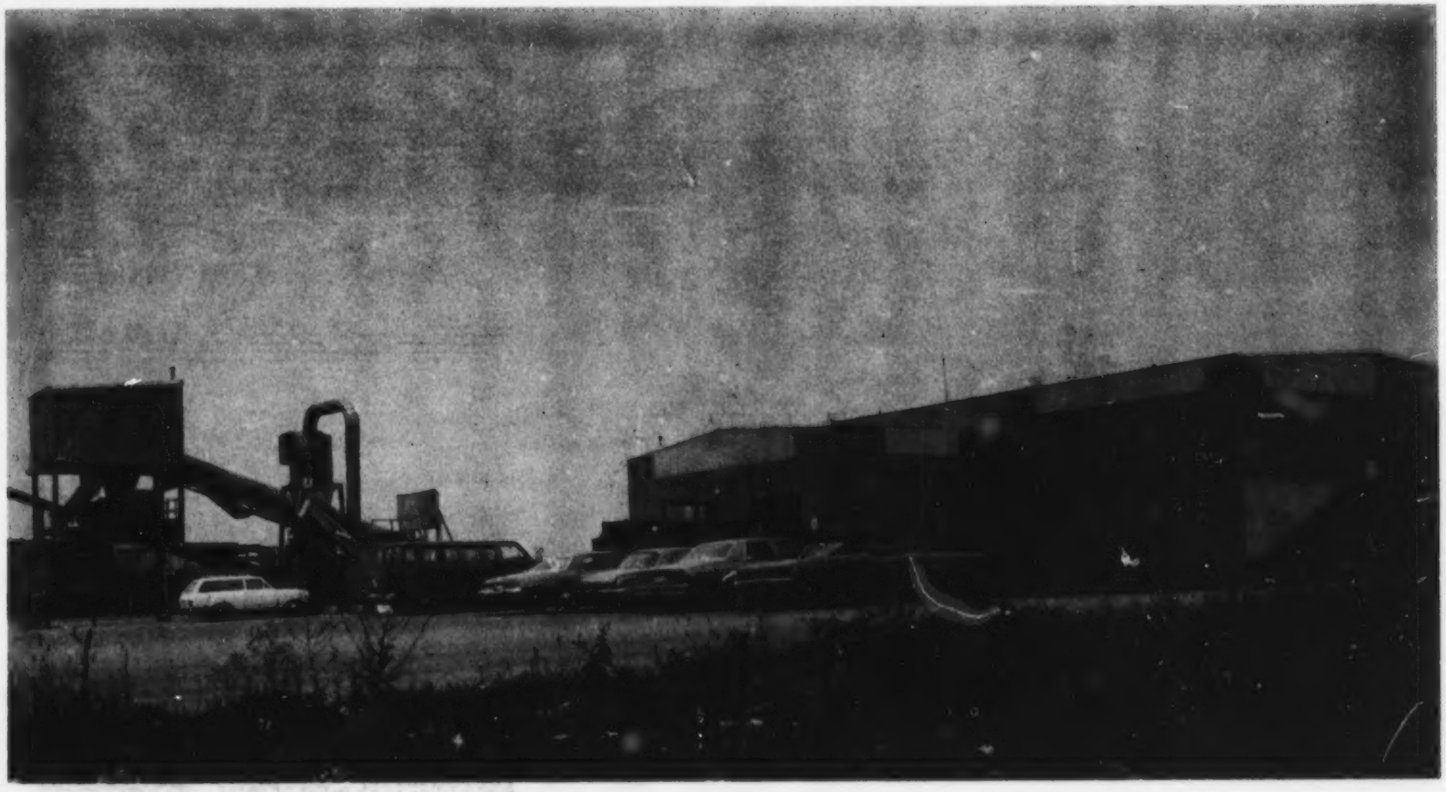


Figure 1. Outagamie County Solid Waste Plant; Appleton, Wisconsin.

Figure 2. West mill at the Appleton site. (feed conveyor and discharge conveyor shown at top and bottom of photograph, respectively)

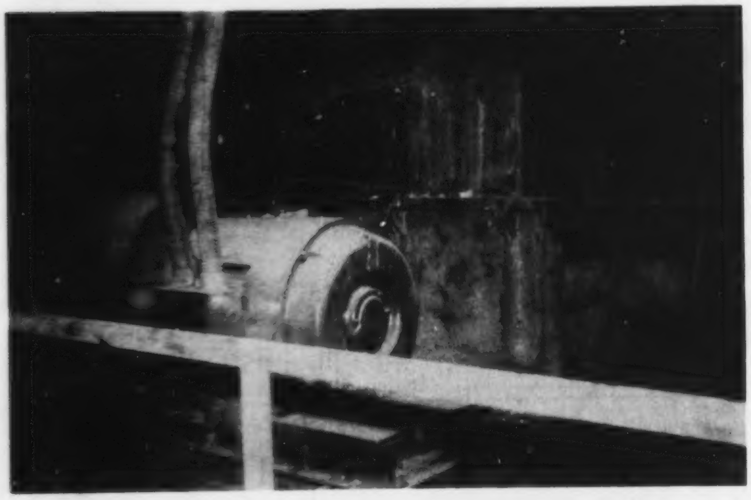


Figure 3. View of west mill and motor (Appleton).

TABLE 2. APPLETON SHREDDER SPECIFICATIONS

Shredder Summary

Item	East	West
Manufacturer	Allis-Chalmers	Allis-Chalmers
Model	KH 12/18	KH 12/18
Grate opening (cm)	12.7 x 30.5	12.7 x 30.5
Number of hammers	24 (4 rows of 6)	48 (4 rows of 12)
Hammer mass (kg)	27	9
Hammer material	US Steel T-1 Type B .12-.21% carbon 22-31 as cast Rockwell C hardness	Carbon steel .4-.5% carbon
Tip to tip diameter (m)	1.23	1.23
RPM	1014	869
Drive	V-belt	V-belt
Tip velocity (m/sec)	65.3	56.0
Freewheeling power (kw)	47.0	41.0

Motor Summary

Item	East	West
Manufacturer	Allis-Chalmers	Allis-Chalmers
Model	114, Type G	114, Type G
RPM	1775	1775
Rating (kw)	298	298
Voltage (volts)	480, 3 phase	480, 3 phase
Current (amps)	462	462

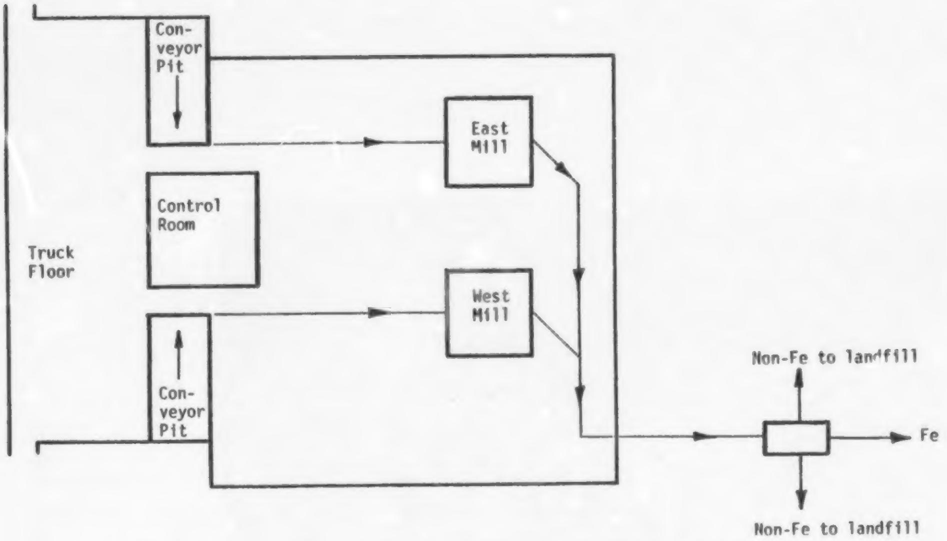


Figure 4. Flow Schematic for Appleton Facility.

Refuse trucks are weighed at the scale house as they enter and leave the site, thus maintaining a record of the total tonnage processed. After initial weighing, trucks enter the building and dump refuse into either one of two receiving pits, the floors of which are steel piano-hinged conveyors. Each receiving conveyor transports refuse to an inclined steel piano-hinged shredder input conveyor. Refuse is visually inspected while it is on the inclined conveyors by plant personnel, and any items which have proven difficult or dangerous to shred are removed. After shredding, the output from both shredders drops onto a horizontal rubber belt discharge conveyor which transports the shredded product to an inclined rubber belt conveyor for removal to the ferrous recovery station. After removal of the ferrous material, the remaining refuse is loaded into transfer trailers for transport to the landfill.

Ames

The Ames Resource Recovery System (Figure 5) in Ames, Iowa, shreds roughly 180 tons of refuse per day through two American Pulverizer Model 6090 horizontal hammermills (Figure 6) operating in series. Both material and energy recovery are practiced at the Ames plant. Most ferrous material is magnetically separated from the refuse after primary shredding, and the remaining material is subjected to secondary shredding and air classification so as to recover a refuse derived fuel. The refuse derived fuel is pneumatically conveyed to the nearby city-owned power plant where it is cofired with coal in the utility's boilers. The plant has the capability of recovering aluminum from the non-ferrous heavy fraction. A summary of the specifications for the shredders at Ames is provided in Table 3, and Figure 7 shows a flow schematic for the Ames facility.

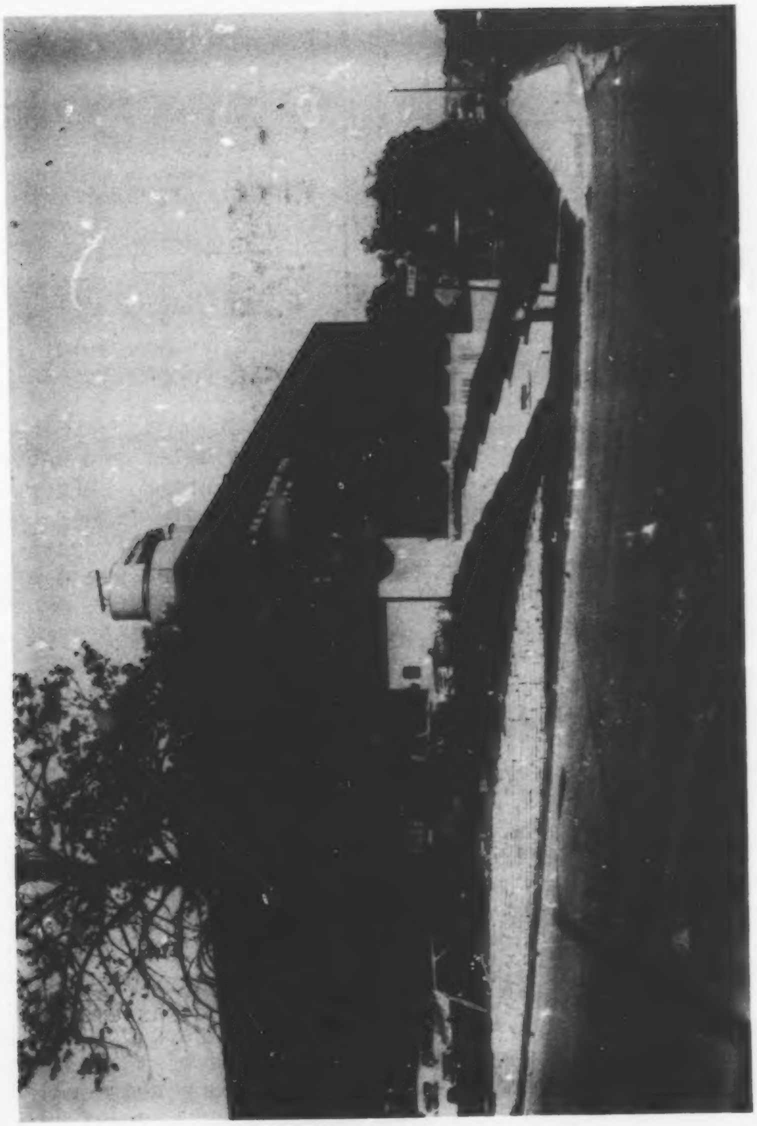


Figure 5. Solid waste recovery system; Ames, Iowa.

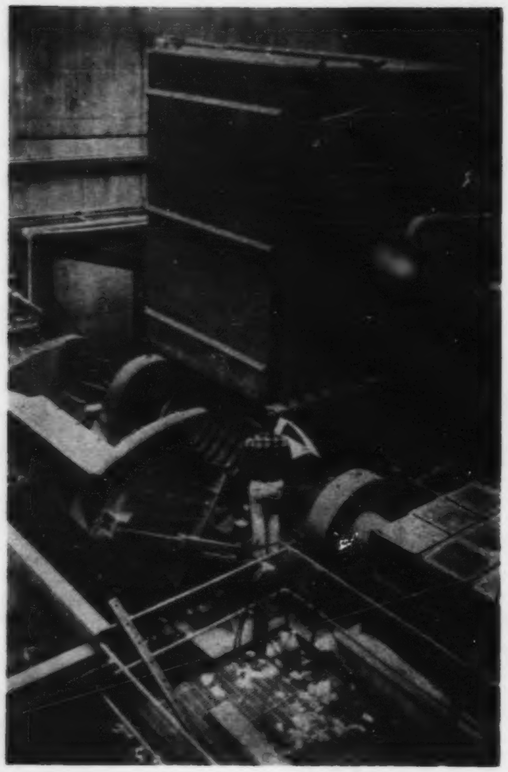


Figure 6. Ames primary shredder shown partially disassembled.

TABLE 3. AMES SHREDDER SPECIFICATIONS

Shredder Summary

Item	Primary	Secondary
Manufacturer	American Pulverizer	American Pulverizer
Model	6090	6090
Grate opening (cm)	22.9 x 25.4	8.9 x 12.7
Number of hammers	48 (4 rows of 12)	48 (4 rows of 12)
Hammer mass (kg)	57	29
Hammer type	Manganese steel 14% manganese	Carbon steel .2% carbon 20 Rockwell C hardness
Tip to tip diameter (m)	1.83	1.83
RPM	691	691
Drive	direct	direct
Tip velocity (m/sec)	55.0	55.0
Freewheeling power (kw)	53.2	40.5

Motor Summary

Item	Primary	Secondary
Manufacturer	Allis-Chalmers	Allis-Chalmers
Model	46791-1	46791-2
RPM	691	691
Rating (kw)	746	746
Voltage (volts)	4160, 3 phase	4160, 3 phase
Current (amps)	151	151

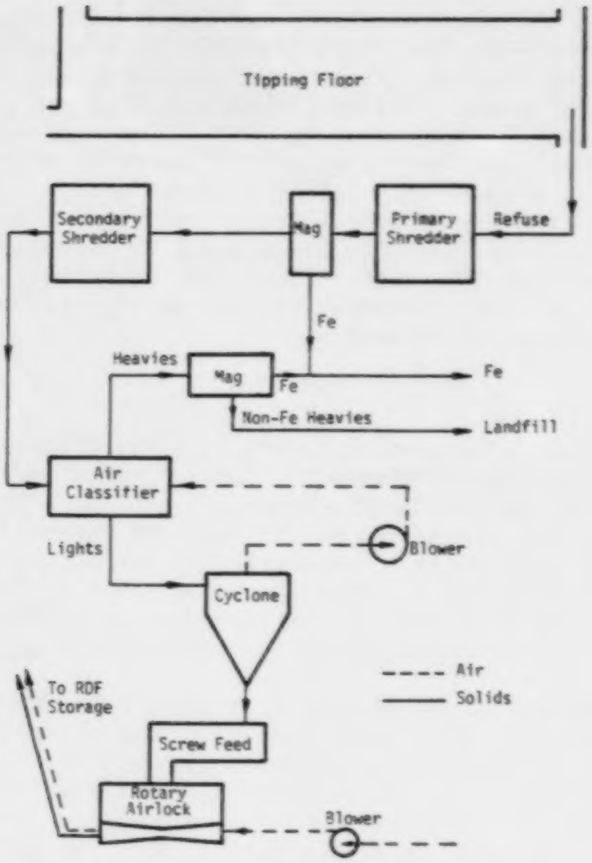

Tipping Floor
Secondary Shredder
Mag
Primary Shredder
Refuse
Fe
Heavies
Mag
Fe
Fe
Non-Fe Heavies
Landfill
Air Classifier
Blower
Lights
Cyclone
Air
Solids
To RDF Storage
Screw Feed
Rotary Airlock
Blower

Figure 7. Flow schematic for Ames plant.

Incoming refuse trucks are weighed at the entrance to the plant and subsequently dump their contents onto a large tipping floor. The refuse is scanned by plant personnel, and any potentially hazardous materials (i.e. gasoline tanks, chemical containers, etc.) are removed. The refuse is then pushed by a front-end loader onto the horizontal feed conveyor for the primary shredder. The shredded refuse is removed from under the primary shredder by a vibratory conveyor which transports the refuse under a magnetic belt conveyor before depositing the non-ferrous refuse on the inclined conveyor which feeds the secondary shredder. A second vibratory conveyor removes material from under the secondary shredder and discharges the material onto an inclined conveyor for transport to a surge bin prior to air classification. An inclined conveyor, which acts as a leveling control, removes material from the surge bin, passes under a scalping roll, and deposits the refuse on a third vibratory conveyor which feeds the shredded refuse into the air classifier through a rotary air lock.

The light fraction is de-entrained from the airstream by a cyclone. From the cyclone discharge, the light fraction is conveyed to a rotary air lock via a twin screw conveyor and conveyed pneumatically under positive pressure to the power plant. The heavy fraction from the air classifier passes through another ferrous recovery stage before the non-ferrous material recovery system. The ferrous component separated after primary shredding is magnetically classified a second time to remove trapped non-ferrous material before joining the ferrous material recovered from the air classified heavy fraction. The final ferrous product is loaded directly into a trailer for removal from the plant. Since the non-ferrous heavy material recovery system is currently inoperative, the non-ferrous heavies are transported to the landfill instead.

Cockeysville

The Baltimore County Resource Recovery Facility (Figure 8) in Cockeysville, Maryland shreds approximately 320 tons of refuse per day through two Tracor Marksman Model A60 horizontal hammermills (Figure 9) operating in parallel. Although the capability exists for both material and energy recovery, currently only magnetic separation of ferrous material is carried out and the remainder of the shredded refuse is taken to the landfill. Table 4 lists the specifications of the shredders at Cockeysville, while Figure 10 presents a flow schematic of the Cockeysville operation.

Incoming refuse trucks are weighed at a scale house before proceeding to dump their contents into one of four hydraulic push pits (two pits for each shredder). Refuse is pushed by a hydraulic ram onto an inclined conveyor which feeds the shredder. As the refuse falls onto the feed conveyor, it is scanned for hazardous material which may be removed by a small set of grapples controlled by the operator in the control pod. Whenever the capacity of the push pits to receive refuse is exceeded, the trucks may dump into a large raw refuse storage pit from which an overhead crane may remove the material during slack operating periods. Shredded material is removed from under the shredder by a short rubber belt conveyor and discharged onto a long, inclined rubber belt conveyor for transport to the ferrous removal station. After ferrous removal, the remaining refuse is loaded into transfer trailers and taken to the landfill.

Great Falls

The Great Falls Solid Waste Reduction Facility (Figure 11) in Great Falls, Montana, operates two Heil vertical shaft hammermills in parallel. The larger of the two is a Heil model 42F (capable of shredding approximately 20 TPH), and the smaller is a Heil model 42D (15 TPH). The combined daily tonnage of the two shredders is typically close to 150 tons. Although the plant is equipped to recover ferrous material, the ferrous recovery stage was not in operation during the course of the tests; hence, all the shredded waste was compacted into transfer trailers and transported to the landfill. Table 5 summarizes the major features of the shredders which are utilized in Great Falls. Since the vertical hammermill has no grates, both

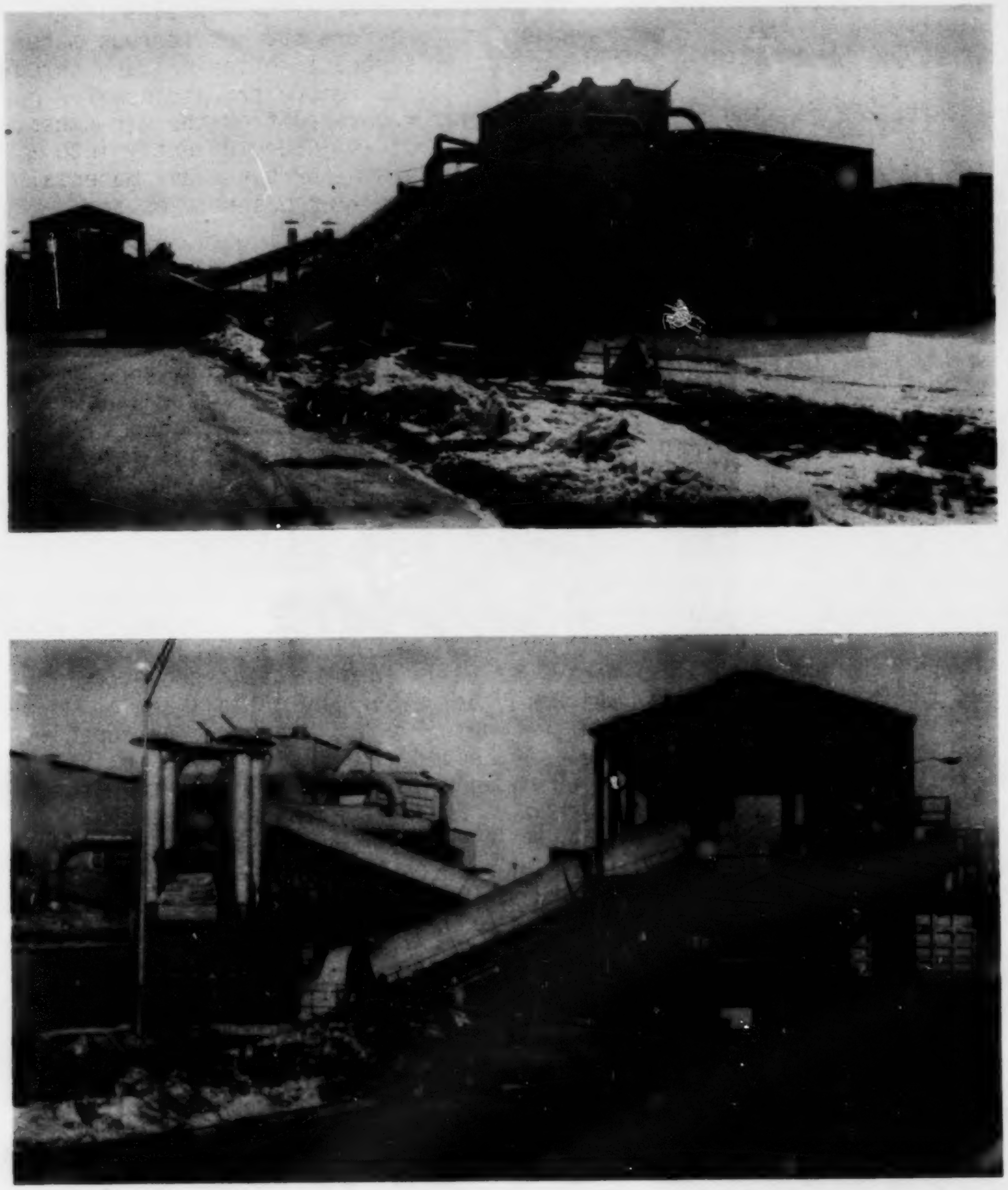


Figure 8. Baltimore County Resource Recovery Facility; Cockeysville, Maryland.

Figure 9. Shredder #1 at Cockeysville.
(shown partially disassembled for hammer change)

TABLE 4. COCKEYSVILLE SHREDDER SPECIFICATIONS

Shredder Summary

Item	#1	#2
Manufacturer	Tracor-Marksman	Tracor-Marksman
Model	A60	A60
Grate opening (cm)	20.3 x 35.6	20.3 x 35.6
Number of hammers	24 (4 rows of 6)	24 (4 rows of 6)
Hammer mass (kg)	73	73
Hammer type	Manganese steel 14% manganese	Manganese steel 14% manganese
Tip to tip diameter (m)	1.52	1.52
RPM	880	880
Drive	direct	direct
Tip velocity (m/sec)	70.0	70.0
Freewheeling power (kw)	64.3 forward, 67.8 reverse	---

Motor Summary

Item	#1	#2
Manufacturer	Toshiba	Toshiba
Model	Type TIM, wound rotor	Type TIM, wound rotor
RPM	880	880
Rating (kw)	746	746
Voltage (volts)	4160, 3 phase	4160, 3 phase
Current (amps)	130	130

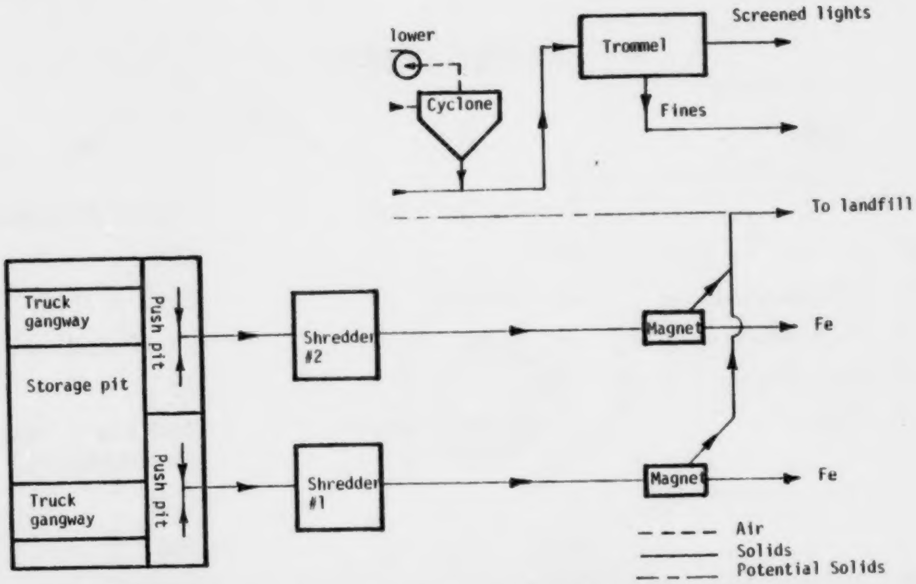

lower
Cyclone
Trommel
Screened lights
Fines
To landfill
Truck gangway
Storage pit
Push pit
Shredder #2
Magnet
Fe
Push pit
Truck gangway
Shredder #1
Magnet
Fe
Air
Solids
Potential Solids

Figure 10. Flow Schematic of Cockeysville Plant

Figure 11. Great Falls Solid Waste Reduction Facility; Great Falls, Montana.

TABLE 5. GREAT FALLS SHREDDER SPECIFICATIONS

Shredder Summary

Item	20 ton	15 ton (not tested)
Manufacturer	Heil	Heil
Model	42F	42D
Smallest hammer clearance (cm)	2.5	2.5
Discharge opening (cm)	91 x 30	91 x 30
Number of hammers	38	34
Hammer mass (kg)	6.5	6.5
Hammer type	1060 steel	1060 steel
Tip to tip diameter (m)	1.22	1.22
RPM	1155	--
Drive	V-belt	V-belt
Tip velocity (m/sec)	73.8	--
Freewheeling power (kw)	21.7	--

Motor Summary

Item	20 ton	15 ton
Manufacturer	Howell Electric Motor	Howell Electric Motor
Model	type BA10 3	--
RPM	1775	--
Rating (kw)	186	149
Voltage (volts)	480, 3 phase	480, 3 phase
Current (amps)	258	--

the clearance between the hammers and the lining as well as the size of the discharge opening are listed instead of the usual grate opening dimensions. All testing of the shredders in Great Falls was done on the Model 42F shredder (Figures 12 and 13). Figure 14 provides a schematic of the Great Falls plant.

As refuse trucks enter the facility, the gross weight is recorded. At the conclusion of each day, the pre-recorded tare weights of the trucks are subtracted from the gross weights, thus providing a record of the daily

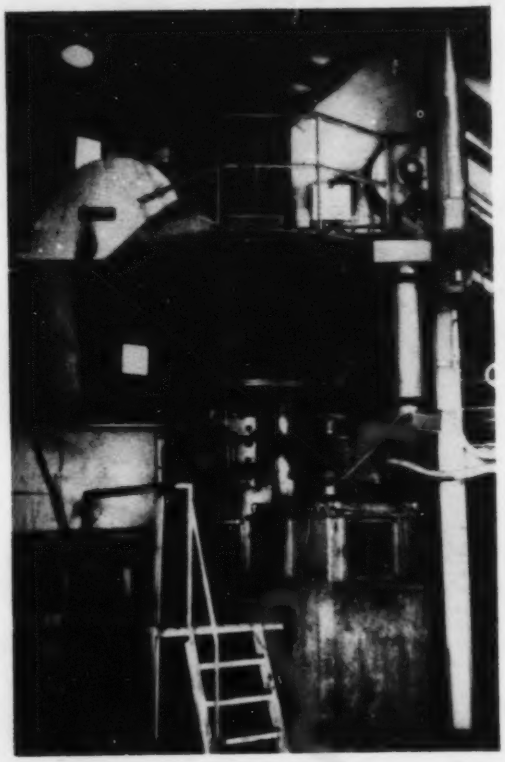


Figure 12. Exterior view of Great Falls vertical hammermill.

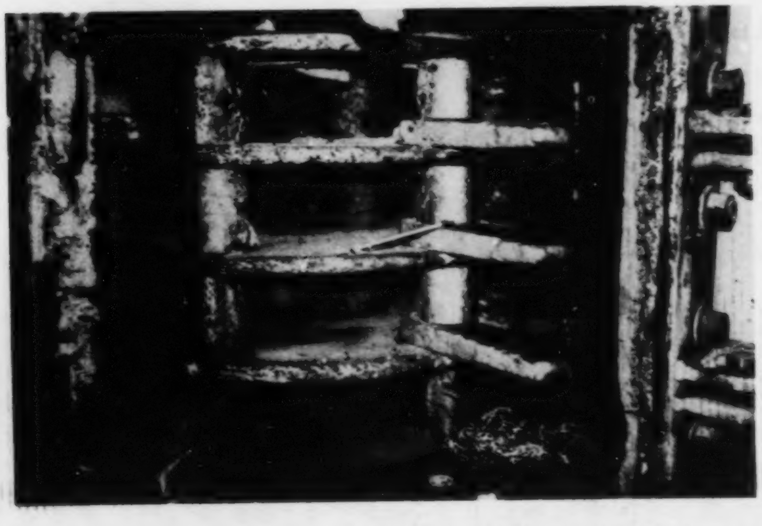


Figure 13. Interior view of Great Falls vertical hammermill.

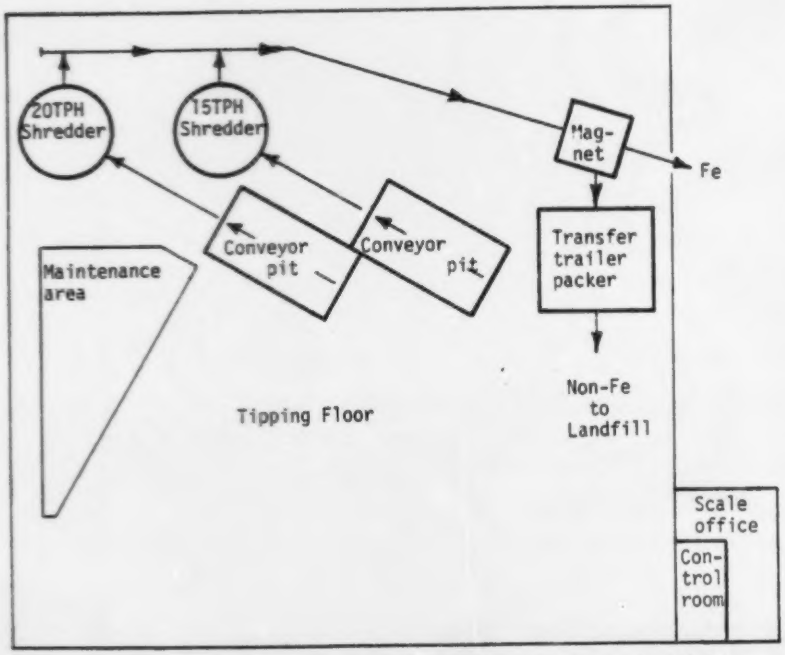


Figure 14. Flow schematic of Great Falls facility.

tonnage. Refuse is dumped by the trucks onto a tipping floor and then pushed by a rubber-tired front end loader into either of the two horizontal steel piano-hinged conveyors. The horizontal conveyors transport the refuse to the inclined shredder input conveyors which are also of steel piano-hinged construction. As the refuse travels up the inclined conveyors, it is visually inspected by the plant personnel so any hazardous or difficult to shred items may be removed. After shredding, the output from both shredders drops onto a horizontal rubber belt discharge conveyor which transports the shredded product to an inclined rubber belt conveyor for removal to the ferrous recovery stage. After removal of the ferrous metal, the remaining material is loaded into transfer trailers for transport to the landfill.

Tinton Falls

The Monmouth County Reclamation Center (Figure 15) in Tinton Falls, New Jersey, operates two Carborundum vertical shaft ring shredders (formerly Eidel Model 1000). Table 6 provides a summary of the major features of the shredders utilized in Tinton Falls. Since vertical shredders do not use grate bars, the clearance between the individual grinders and the lining along with the size of the discharge opening are listed. A central tipping floor serves both shredders (which are located in separate rooms on opposite sides of the tipping room). The separation of the shredders permits maintenance and repair of one shredder to be accomplished in a relatively clean

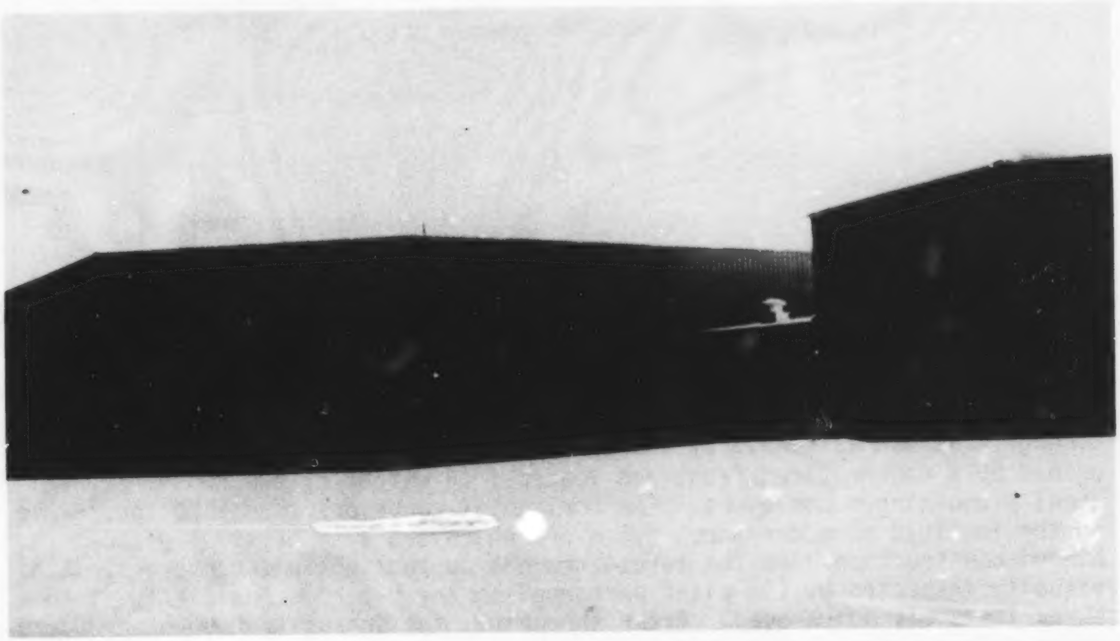


Figure 15. Monmouth County Reclamation Center;
Tinton Falls, New Jersey

TABLE 6. TINTON FALLS SHREDDER SPECIFICATIONS

Shredder Summary

Item	Plant 2 (Plant 1 identical)
Manufacturer	Carborundum
Model	1000
Smallest grinder clearance (cm)	5 (at time of test)
Discharge opening (cm)	66 x 35.6
Number of grinders	60
Grinder mass (kg)	28.1
Grinder type	nickel-manganese steel
Tip to tip diameter (m)	1.5
RPM	369
Drive	gear
Tip velocity (m/sec)	29.0
Freewheeling power (kw)	38.5

Motor Summary

Item	Starter motor	Drive motor (2 required)
Manufacturer	Allis-Chalmers	Westinghouse
Model	124	ABDP
RPM	1770	1746
Rating (kw)	75	373
Voltage (volts)	460, 3 phase	460, 3 phase
Current (amps)	116	563

and quiet environment while shredding is done in the opposite end of the plant. Normally, a shredder is operated for approximately five weeks before it is taken off line. During the five weeks one shredder is operating, the other shredder is idle so maintenance can be performed. Nine hundred fifteen tons is typical of the total refuse received in one week. Figure 16 shows the interior of Plant 2 (where the tests were done) from the entrance of the feed conveyor to almost the exit of the rubber discharge conveyor. A view of the interior of the shredder in Plant 2 is presented in Figure 17. Figure 18 shows a schematic of the entire Reclamation Center.

Trucks are weighed both as they enter and as they leave the facility in order to maintain a record of the daily tonnage. The trucks dump onto a tipping floor from which a small rubber-tired loader can push the refuse onto a horizontal steel conveyor serving one of the shredders. The horizontal conveyor loads an inclined section of the steel feed conveyor. As shown

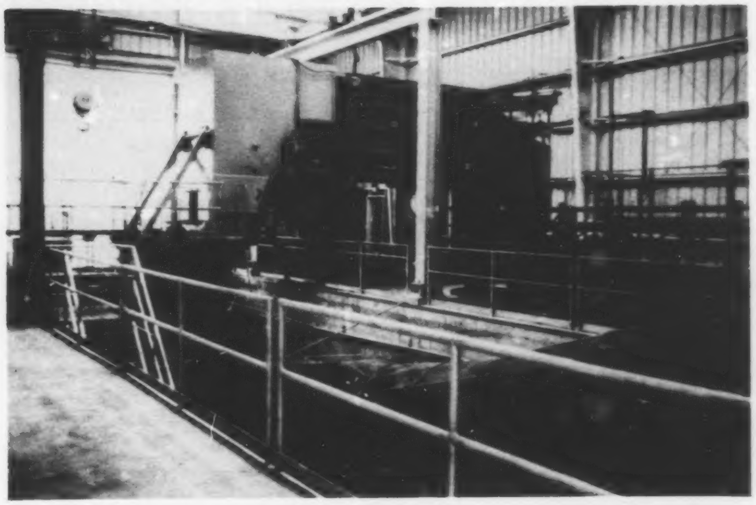


Figure 16. Interior of Monmouth County Reclamation Center, Plant 2.

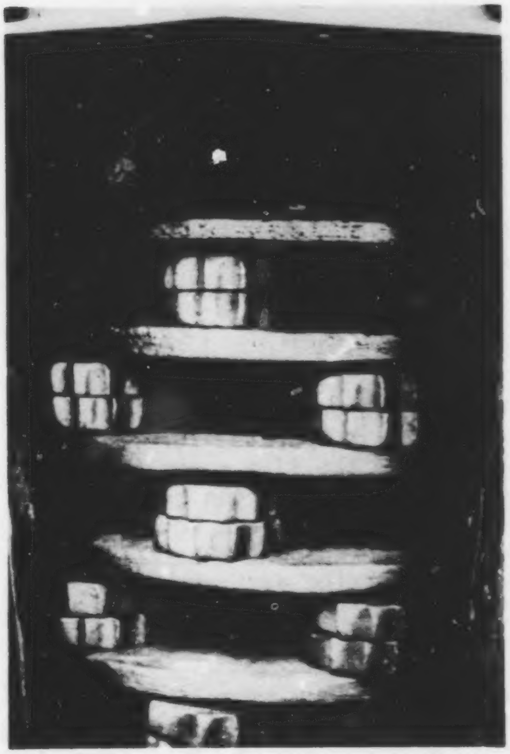


Figure 17. Interior of vertical ring shredder.

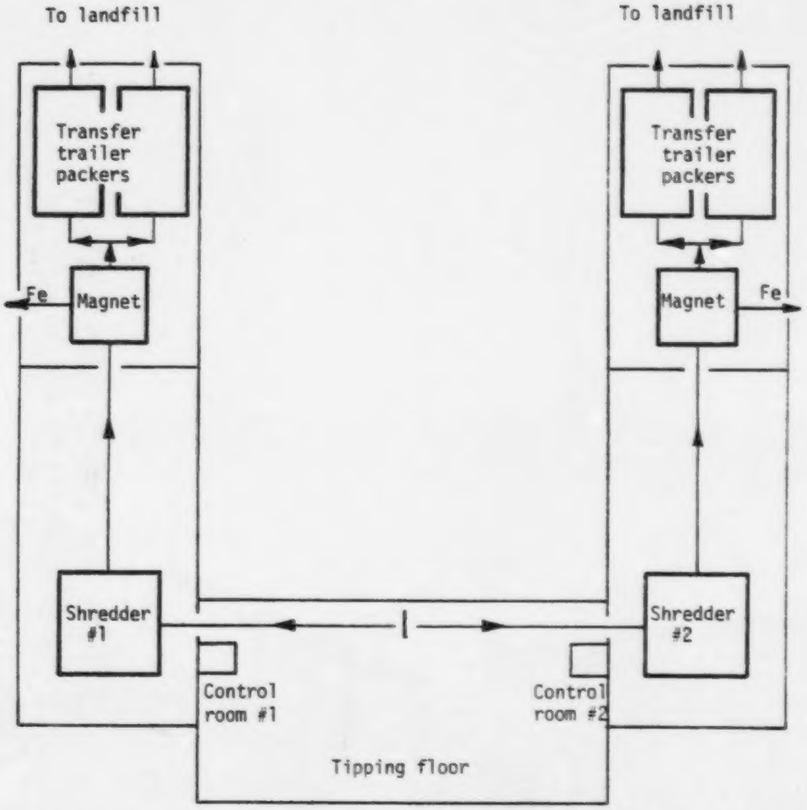

To landfill
To landfill
Transfer trailer packers
Transfer trailer packers
Fe
Magnet
Magnet
Fe
Shredder #1
Shredder #2
Control room #1
Control room #2
Tipping floor

Figure 18. Flow schematic of Tinton Falls facility.

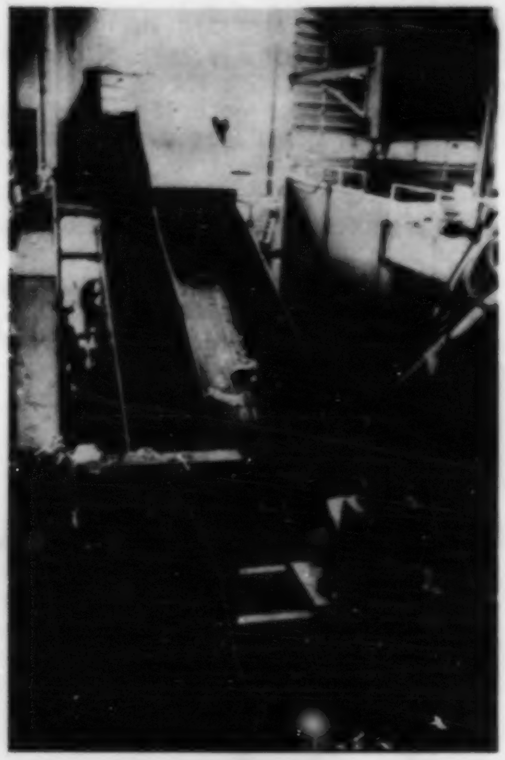
in Figure 16, the inclined section of the feed conveyor is followed by a horizontal section prior to depositing refuse in the shredder. After shredding, the output of the shredder is transported by a rubber belt conveyor through a ferrous recovery stage to the hopper used to load the transfer trailers, which carry the shredded product to the adjoining landfill.

Energy, size, and wear measurements were collected for shredder #2 only.

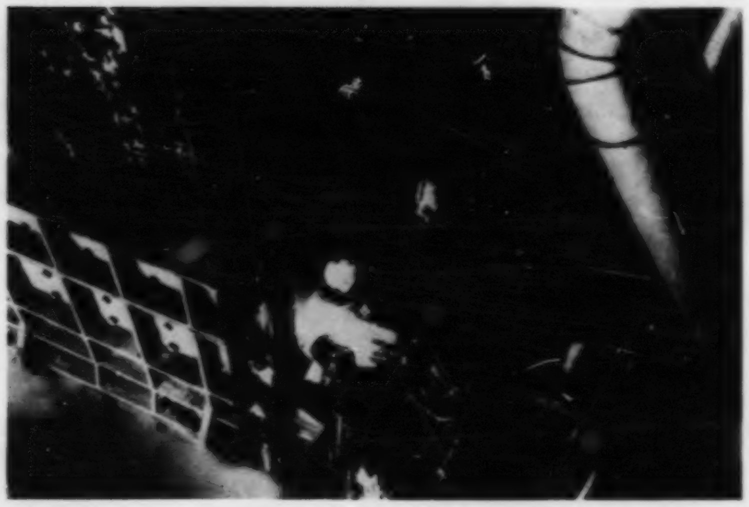
Odessa

The City of Odessa Solid Waste Management Facility (Figure 19) in Odessa, Texas, has a single Newell model 68 horizontal hammermill (Figure 20) in operation. Approximately 230 tons of refuse are shredded on a typical day. The plant is equipped to recover ferrous material and pack the shredded

Figure 19. City of Odessa Solid Waste Management Facility; Odessa, Texas



a. upper portion including feed conveyor



b. lower portion

Figure 20. Odessa horizontal hammermill.

refuse into transfer trailers for transport to the landfill. The major features of the Newell shredder are summarized in Table 7. A schematic of the Odessa facility is provided in Figure 21.

Records of the net tons of refuse entering the facility are maintained in the scalehouse. After weighing, trucks dump their contents onto the tipping room floor. A rubber-tired front end loader pushes the refuse from the tipping floor into either one of two opposing hydraulic push pits. As the moving wall of the push pit approaches the rubber belt feed conveyor, refuse is forced onto the belt. A small grapple is situated near the juncture of the push pits and feed conveyor in order to pick out hazardous items and help control the flow of refuse from the push pits. After shredding, the refuse is discharged onto a second rubber belt conveyor which transports the refuse to the ferrous recovery station. After ferrous removal, the refuse is dropped into a packer unit which packs the shredded product into transfer trailers for transport to the landfill.

HAMMER MAINTENANCE PROGRAMS

The Appleton, Cockeysville, and Great Falls plants utilize a program of hammer retipping as a means of extending hammer life (Figures 22-23). At Appleton, welding wire is normally used instead of electrode rods. Stoody 110 is used for building up the hammer surface prior to an application of one or two passes of Stoody 134 hardfacing. Stoody 134 is the wire equivalent of the Stoody 2134 electrode which was used as part of the wear experiments at Appleton.

The Cockeysville facility used McKay 118 for buildup of the hammers, followed by an application of one or two passes of McKay 55. Both of these alloys are applied in electrode form. McKay 55 was one of the alloys used in the wear experiments at the Cockeysville plant.

In order to reduce manpower and time requirements for hammer changes, a pin puller (Figure 24) is used at Cockeysville for removing the hammer pins. This hydraulic unit eliminates the need for various "brute force" methods, icluding the use of sledge hammers and come-alongs.

The Great Falls facility normally uses Amsco Super 20 electrode to retip the 1060 carbon steel hammers. Stoody 2134 was also used in the wear experiments in Great Falls in order to compare with the Appleton results.

Hammer retipping is not practiced at either the Ames or Odessa plant. At the time of the tests, the operating procedure at Ames and Odessa was to wear the hammers in the shredders until refuse was no longer shredded effectively (indicated by lower throughput and larger particle size). The worn hammers were then removed, scrapped, and replaced by new hammers (Figures 25-28). The plant located in Tinton Falls scraps the used ring grinders (Figure 29) when the product particles become excessively large. Contrary to the case of horizontal hammermills, the throughput increases when the shredding elements wear out. Unlike the grinders, the shredder breaker bars were regularly resurfaced in order to extend their life as were the sweep plates in the bottom of the shredder.

TABLE 7. ODESSA SHREDDER SPECIFICATIONS

Shredder Summary

Item	
Manufacturer	Newell
Model	68
Grate opening (cm)	35.6 x 24.1
Number of hammers	14
Hammer mass (kg)	67
Hammer type	manganese steel
Tip to tip diameter (m)	1.5
RPM	880
Drive	direct
Tip velocity (m/sec)	69.1
Freewheeling power (kw)	101.7

Motor Summary

Item	
Manufacturer	Toshiba
Model	TIM-VCK-V
RPM	880
Rating (kw)	373
Voltage (volts)	2400, 3 phase
Current (amps)	295

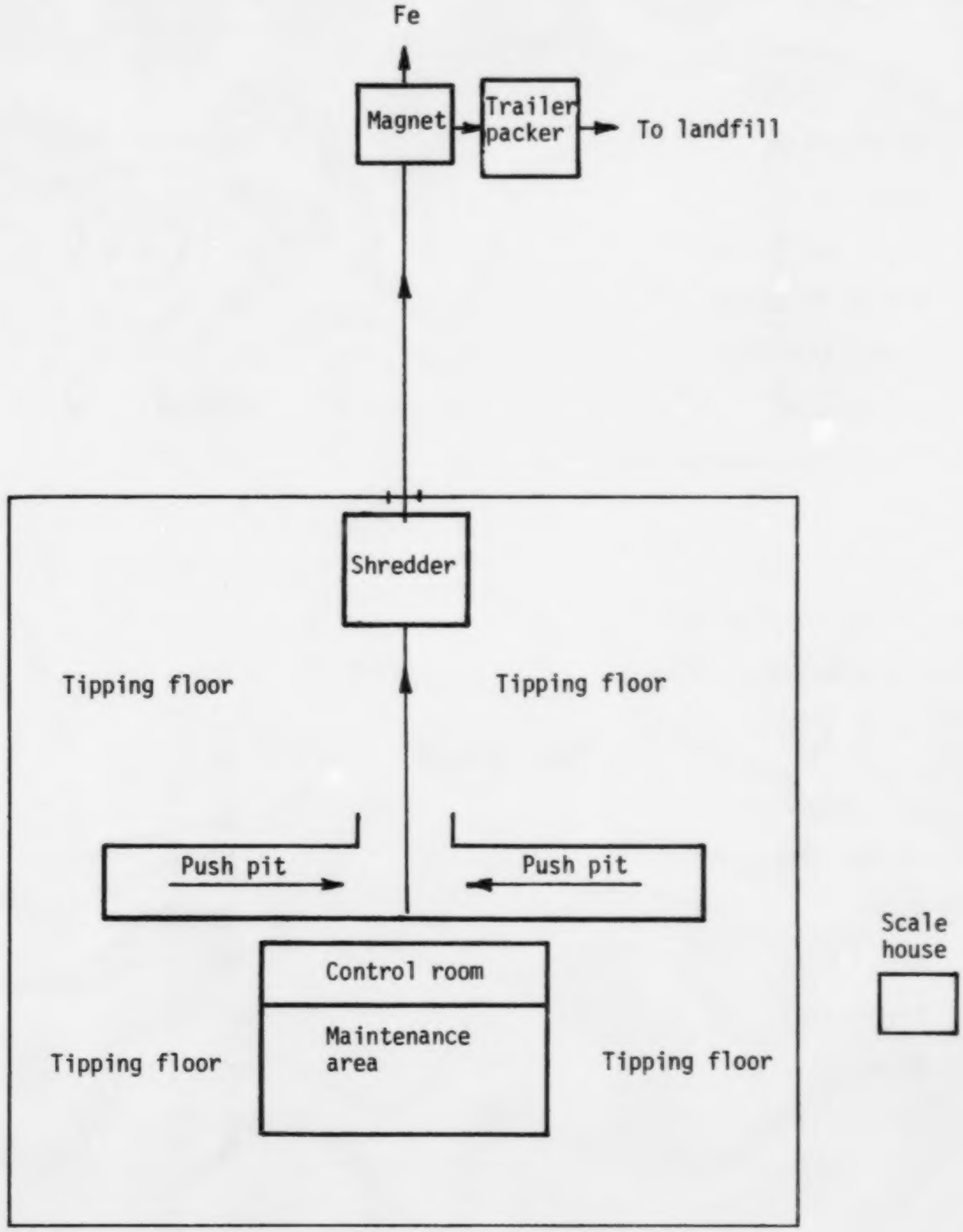

Fe
Magnet
Trailer packer
To landfill
Shredder
Tipping floor
Tipping floor
Push pit
Push pit
Control room
Maintenance area
Tipping floor
Tipping floor
Scale house

Figure 21. Flow schematic of Odessa facility.

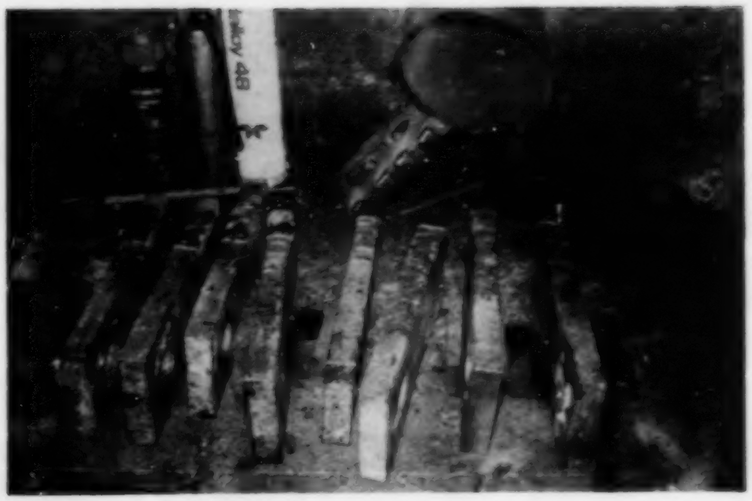


Figure 22. Hammers undergoing hardfacing at Appleton. Weld deposits are shown on hammer tips.

Figure 23. Hardfacing application at the Cockeysville facility.

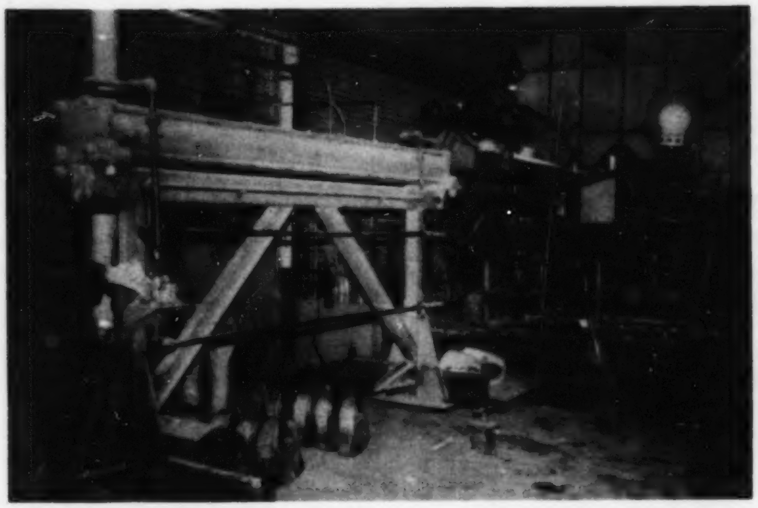


Figure 24. Utilization of pin puller for hammer changes

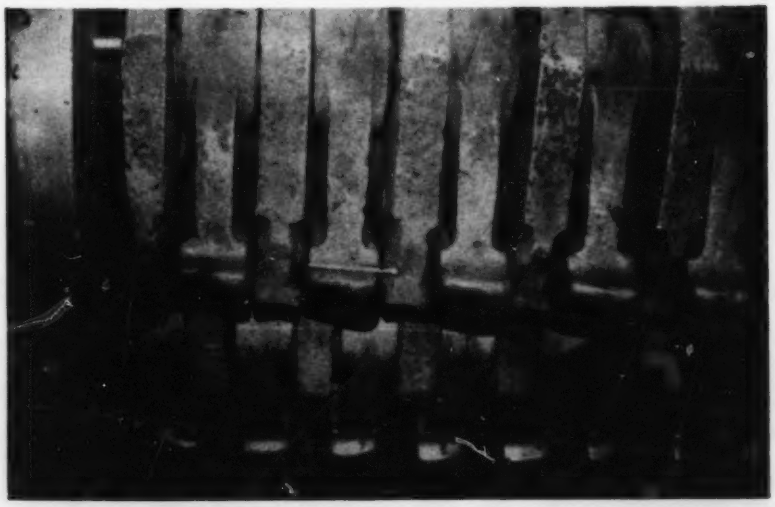


Figure 25. View of hammers in Ames primary shredder.
(note uneven pattern of wear among hammers and
pencil resting on hammer for reference of scale)

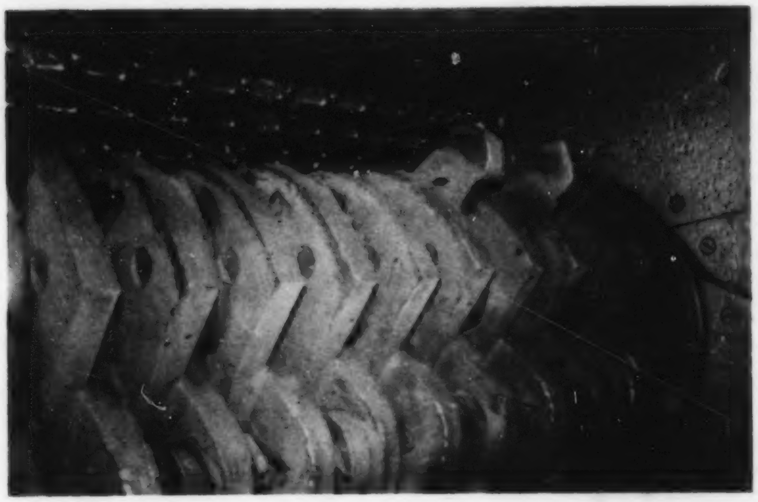


Figure 26. Inside view of Ames secondary shredder.
(note severe wear of hammers shown in right center of photograph)

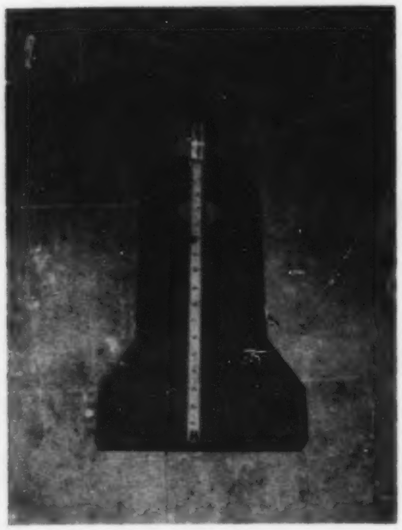


Figure 27. New hammer for Ames secondary shredder.

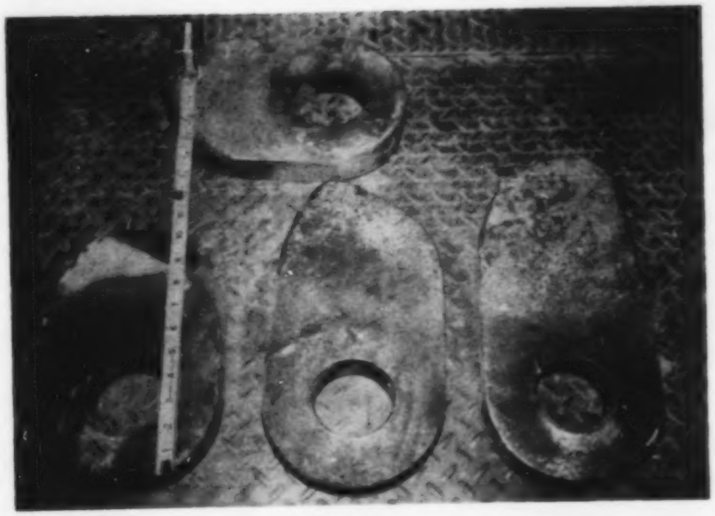


Figure 28. Worn hammers from Ames secondary shredder.
(tape is extended to length of new hammer)

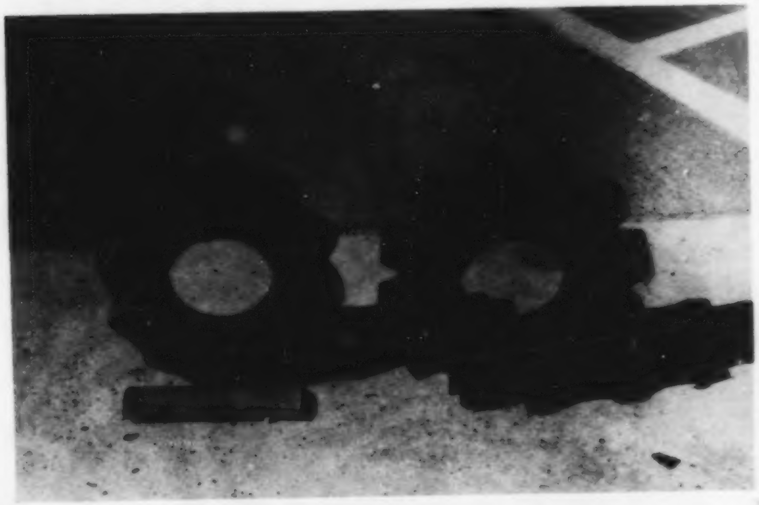


Figure 29. Used and new ring grinders for Tinton Falls vertical shredder.

SECTION 2

FINDINGS AND CONCLUSIONS

In the study reported herein shredders at six large-scale refuse processing plants are evaluated. In-plant operational data were collected from nine shredders: namely seven horizontal hammermills, a vertical hammermill, and a vertical ring shredder.

The main objectives of this study were to: 1) determine shredder performance, and 2) develop theoretical relationships that describe shredder operation and performance.

Emphasis was placed on the development of analytical relationships such that the shredders could be compared on the same basis. Consequently, many of the findings are necessarily mathematical in nature. The mathematical relationships make possible a comparison of shredders on the hypothetical basis that the products of all the shredders have the same average particle size. In this manner shredders can be compared even though under actual circumstances each shredder may produce a somewhat different range of particle sizes.

Where possible, shredder performance was explained by deriving governing relationships, utilizing key parameters of size reduction such as energy consumption, throughput, and particle size. These relationships would be of interest primarily to those concerned with shredder design, operation, and optimization.

Some results of the study are of interest not only to those peripherally involved with shredding as a unit operation but also to those involved in the overall requirements of a refuse processing plant, e.g., Directors of Public Works and Plant Supervisors.

General findings that are of interest to those involved in plant management (i.e. the user community) are:

1. Costs associated with primary size reduction of refuse to nominal product size in the range of 6 to 12 cm are estimated to be as follows:

    a. Energy = \$0.08 to \$0.20 per ton of refuse

    b. Hammer Maintenance = \$0.40 per ton of refuse.

2. On the basis of the data collected in the investigation, and assuming an equivalent average particle size production, only a few minor differences

could be found in the energy consumption by and the hammer wear in the following four shredders:

a. Allis Chalmers horizontal hammermill;

b. Tracor-Marksman horizontal hammermill;

c. American Pulverizer horizontal hammermill; and

d. Heil vertical hammermill.

3. In comparison to the preceding four shredders, the Newell horizontal hammermill and the Carborundun vertical ring shredder had relatively low energy requirements. On the basis of the production of an average characteristic particle size of 2.1 cm, the Newell shredder at Odessa uses 1.1 kwh/T. A similar shredder, the Tracor-Marksman located in Cockeysville, requires 8.9 kwh/T. It seems as though the relatively low energy requirement by the Newell shredder is due primarily to the number of hammers used for the shredding rather than to an inherently superior shredder design. The Newell shredder uses 14 hammers as opposed to the 24 to 48 hammers used by the other hammermills.

4. For a given shredding operation and from the standpoint of cost, the two following hammer maintenance programs are judged equivalent:

a. build-up and/or hardfacing of hammers (build-up method); and

b. the use of hammers until they no longer effectively shred refuse, after which they are replaced (wear-and-scrap method).

Since the cost of the two maintenance programs are equal to each other, the build-up method of hammer maintenance is to be preferred. The rationale for this choice is that regularly built-up hammers produce a uniform shred size throughout the course of shredding large quantities of refuse, and yet do not unduly affect energy consumption and throughput capacity.

In addition to the preceding general findings, a number of specific findings deal with energy requirements of shredding, hammer wear, and with functional relationships among shredding parameters. These specific results are of interest primarily to those concerned with shredder design, operation, and optimization, and they are the subject matter of the remainder of this section.

ENERGY AND PARTICLE SIZE

5. Mathematical expressions that describe the functional relationship of power draw, throughput, and moisture content of shredded waste can be established for each shredder. These relationships can be expressed in the general form:

$$P_N = a\dot{m}_w^r (1 - MC)^s \quad (1)$$

where: P_N = net power
$\dot{m}_w$ = throughput on a wet weight basis
MC = air dry moisture content,

and a, r, and s are experimentally determined constants. The range for these constants for the shredders tested are $0.14 \leq a \leq 47.04$, $0.27 \leq r \leq 1.92$, and $-12.64 \leq s \leq 4.79$.

6. Mathematical expressions have been developed that relate average specific energy consumption to average size of the shredded product. These relationships have the form:

$$E_o = bX^u \quad (2)$$

where: E_o = specific energy,
X = product size, expressed as either characteristic or nominal product size;

and b and u are analytically determined constants. Values of u were found to be in the range, $-0.92 \leq u \leq -0.81$.

7. Through the testing and evaluation program valuable data were obtained regarding the efficiency of single versus multiple-stage size reduction. In particular, evaluation of the data collected for the two shredders in series at Ames showed a significantly greater gross specific energy consumption in comparison to that in the single-stage size reduction practiced at the Cockeysville facility. However, this result must be viewed with reservation, since the shredding lines at Ames and Cockeysville have not been shown to represent an optimum configuration for either multiple-stage or single-stage shredding.

8. The fact that the secondary shredder at Ames used approximately twice as much energy as the primary shredder supports the assumption that the shredder line at Ames has not been optimized. Through appropriate manipulation of grate openings in both shredders, it might be possible to develop a more energy efficient shredding operation at the Ames facility.

9. Apparently a definite inverse relationship exists between the size of the shredded material and the rate of material flow through each shredder. This relationship, though only qualitatively established in the present research, supports previous data from research conducted at the University of California, Berkeley. From the standpoint of efficient and reliable processing and separation of materials by downstream unit processes, the prediction, manipulation, and control of shredded product size are of obvious importance. Results of this research indicate that for a particular set of shredder characteristics (e.g. grate opening, rpm, etc.), an increase in throughput will result in a decrease in product size.

HAMMER WEAR

10. The optimum hardness range for hardfacing alloys appears to be in the range of 48 to 56 Rockwell C. Severe hammer wear is encountered at the lower levels of hardness for base hammer material and hardfacing alloys.

11. Proper testing and evaluation of the performance of hardfacing alloys requires a standardized test procedure that evaluates the hardfacings under identical operating conditions.

12. Prudent selection of hardfacing alloys can result in significant reductions in hammer wear (typically 25 percent) and can lead to an increase in the amount of time required between hardfacing applications and hammer changes, or both.

13. The upper limit of alloy hardness for size reduction of MSW is governed by the chipping tendency of alloys under impact loading.

14. The degree of chipping of hard alloys appears to be a function of the particular composition of each alloy and of the type of wastes being shredded. Consequently, the proper selection of hardfacing requires that several hard alloys be tested and evaluated in order to ascertain the best alloy for a particular shredding application.

15. Proper hammer maintenance calls for the measurement of wear and a calculation of rates of wear such that in the interval between hardfacing applications, hammers are limited to the maximum shredded tonnage at which the hardfacing weld deposits will be removed. With such a program, wear will be confined primarily to the hardfacing, and consequently minimum rates of overall wear will occur because of the preventing of wear of the softer base metal of the hammer with its concomitant higher rate of wear.

16. To take into consideration the different degrees of size reduction between the test sites, a means of normalization and comparison of hammer wear data was formulated that accounts for variations in size of the feed material and size of the shredded product for different shredders.

SECTION 3

RECOMMENDATIONS

Several recommendations can be presented with regard to areas of research that would extend the knowledge of the science of size reduction of MSW, while at the same time result in a potential reduction of operational and maintenance costs for shredding operations. These recommendations are presented, along with the rationales for them. A number of the recommendations are aimed specifically at the control of the shredding operation.

1. From the standpoint of efficient energy utilization, the single most important outcome of this study involves the finding that the number of hammers appears to have a significant influence upon the specific energy (kwh/T) required for size reduction of refuse. The data indicate that the possibility exists for minimizing energy consumption through selection of the appropriate number of hammers. Consequently, further testing is needed to establish the influence of the number of hammers upon energy consumption and throughput. Such testing would involve energy and throughput measurement for several different hammer complements, for example, 48, 24, and 12 hammers. Testing at one site should provide enough data to allow a determination of the effect of the number of hammers upon energy consumption and throughput.

2. An evaluation of the data collected at the city of Ames, Iowa, indicated that the primary shredder uses significantly less energy than does the secondary shredder. Moreover, a comparison of the data from Cockeysville with that from Ames shows that single shredding can be more energy efficient than two-stage shredding. However, it is not known whether or not the processing line at Ames is optimized with regard to energy consumption. The discrepancy in energy requirements between primary and secondary shredders leaves room for doubt that the shredding operation is optimized. Consequently, a test program to determine the best operating conditions for the Ames shredding process is recommended. Suggestions for this program include the varying of the following parameters: 1) grate openings in each shredder, 2) number and length of hammers, and 3) throughput under different test conditions. In addition, comparative data from another site that has a multiple stage size reduction, e.g. Lane County, Oregon, would be useful. At least two sets of data are necessary in order to determine whether or not multiple stage size reduction is more energy efficient than single stage size reduction. Such test programs are needed before a definitive answer can be provided for settling the argument concerning single versus multiple stage size reduction.

3. Inasmuch as in the present study only the hammer wear resulting from primary shredding was characterized, an extension of hammer wear evaluation to include secondary shredding would serve to establish possible avenues for minimization of hammer wear. In particular, the selection of proper grate openings for multiple stage shredding operations needs to be addressed. One of the important consequences of grate opening manipulation in primary and secondary shredders could be a significant reduction in hammer wear. The hammer wear test programs for secondary shredders could be combined with the test programs for evaluating energy requirements for multiple stage size reduction (per item 2). Possible sites include the Ames and Lane County facilities. Upon completion of the hammer wear and energy consumption test programs for both single and multiple stage size reduction, process optimization for shredding, based upon considerations of hammer wear and energy consumption, could be accomplished, while simultaneously, predictive criteria could be established.

4. In light of the fact that shredder holdup (material within the shredder at any instant in time) can be related analytically to throughput and energy consumption, additional collection of shredder holdup data is warranted. Research on shredder holdup would make possible a determination of the influence of machine characteristics upon energy utilization and throughput. Holdup data is seen as the link between the power equation,

$$P_N = a\dot{m}_w^r (1 - MC)^s$$

and the basic physical characteristics of shredders, as for example, grate size, internal machine geometry, and number and geometry of hammers.

SECTION 4

MATERIALS AND METHODS

POWER MONITORING INSTRUMENTATION

The power monitoring equipment includes a Scientific Columbus Model DL34-2K5A2-AY-6070 watt/watt-hour transducer, a Houston Instruments Model 3000 chart recorder, and a digital dividing circuit (Figure 30). Since the nominal inputs to the transducer are 75 to 135 volts and 0 to 6.5 amperes, transformers are required to reduce the line voltage and shredder current to these levels (Figure 31).

The transducer itself has three separate elements and is adaptable to single phase, three phase-three wire, and three phase-four wire systems. Two output signals are provided by the transducer. The first is an analog current signal which is directly proportional to power and may range from zero at no load to one milliamp at full load with all three elements in use. A full load one milliamp signal corresponds to 500 watts per element or 1500 watts total on the secondary (transducer) side of the current and potential transformers. The analog current signal is passed through a precision 1000 ohm resistor which converts the current signal to a voltage signal related to the current by Ohm's Law, $E = IR$. The voltage drop across the resistor is recorded on the chart recorder to provide both a time base and a permanent, continuous record of the power requirements. The power required by the shredder can be found by multiplying the power on the secondary side of the monitoring equipment by the product of the potential and current transformer ratios.

The second transducer output is a digital signal directly proportional to the integral of power over time or, in other words, energy. The transducer has a constant internal count rate of 2160 counts per hour with full load. Dividing the full load rated analog output by 2160 indicates the number of watt-hours each output pulse represents. Again, multiplying by the product of the potential and current transformer ratios determines the energy used on the primary side of the transformers. The digital signal is sent to the dividing circuit, which counts the pulses and triggers an event marker on the chart recorder after a predetermined number of pulses have been accumulated. The divider may be set manually to count between 1 and 9999 input pulses before triggering the event marker.

The general layout of the power monitoring equipment is presented in Figure 32. Since the voltage and current requirements of the shredders varied from site to site, the transformer ratios used at each site are listed in Table 8.

Figure 30. Power monitoring equipment; Appleton.
(shown left to right: dividing unit, chart recorder, transducer)

Figure 31. Installation of voltage and current transformers; Appleton.
(motor control box)

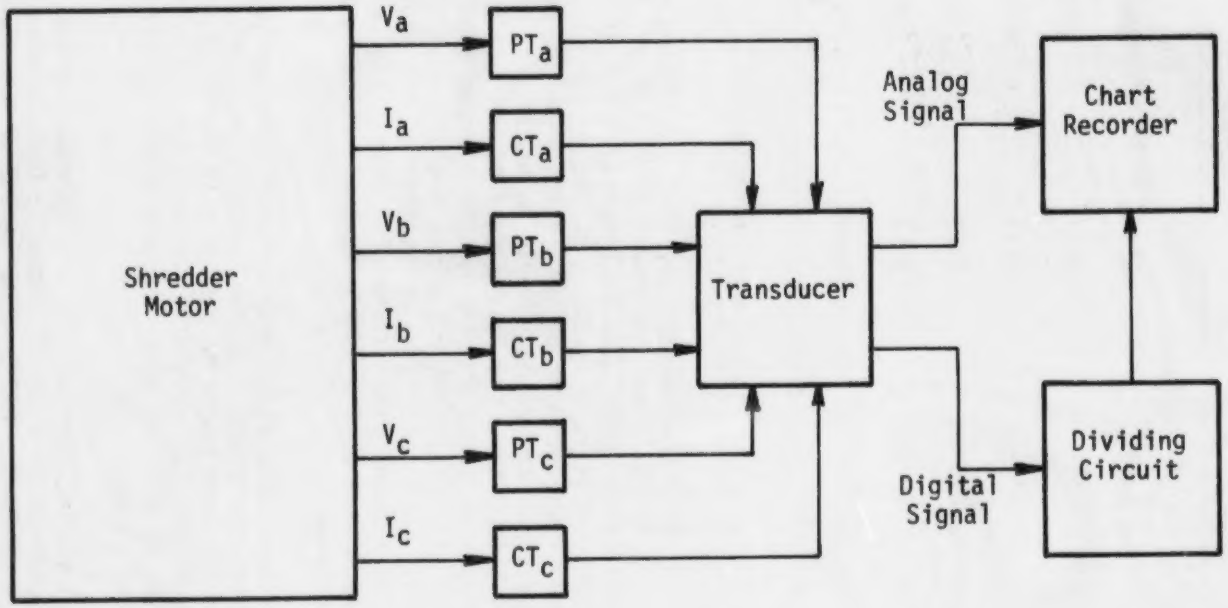

Shredder Motor
V_a
I_a
V_b
I_b
V_c
I_c
PT_a
CT_a
PT_b
CT_b
PT_c
CT_c
Transducer
Analog Signal
Digital Signal
Chart Recorder
Dividing Circuit

Figure 32. Schematic layout of power monitoring equipment.

TABLE 8. TRANSFORMER RATIOS USED AT EACH SITE

Site	Voltage ratio, R_v	Voltage ratio R_c	Product R_vR_c
Appleton	2.4:1	100:1	240:1
Ames	20:1	40:1	800:1
Cockeysville	20:1	20:1	400:1
Great Falls	2.4:1	60:1	144:1
Tinton Falls	2.4:1	120:1	288:1
Odessa	20:1	60:1	1200:1

OTHER EQUIPMENT

A Chronos model 3-ST digital chronometer was used for making any necessary measurements of time. The 3-ST has two modes of operation, Taylor/Sequential and Split/Cumulative. Under Taylor/Sequential operation, the elapsed time between each successive activation of the master control button is displayed. In the Split/Cumulative mode, the first time the master control button is pushed the clock and display begin to accumulate time starting at 0.0 seconds. The second time the master control button is pushed the display stops accumulating time (thus indicating the elapsed time from when the master control button was first pressed) while the internal clock continues to accumulate time. Each succeeding activation of the master control button will then cause the elapsed time between the moment the chronometer initially started and the moment of the most recent operation of the master control button to be displayed.

Conveyor belt speeds were determined with a Power Instruments, Inc. TAK-ETTE model 1707 digital rpm gauge. A disc, exactly one foot in circumference, allowed reading the belt speed in feet/minute directly from the display. An alternative method for obtaining the belt speed was to measure the time necessary for the belt to traverse a known distance, and then divide the distance by the elapsed time.

In order to obtain size distributions for the shredded refuse samples, the samples were first screened on a set of manually held screens having square wire mesh openings of 20.32, 10.16, 5.08, and 2.54 centimeters. Screening of the undersize from the 2.54 centimeter hand held screen was carried out on a SWECO model LS 18533333 Vibro-Energy Rotary Screen. The SWECO was equipped with a series of square wire mesh screens having openings of 2.54, 1.59, 0.95, 0.51, 0.27, and 0.13 centimeters.

SIZE DISTRIBUTION ANALYSIS

The samples were weighed and air dried to a constant weight in a drying room (ambient conditions, 22° C and 65 percent relative humidity) after which the samples were reweighed to permit determination of the moisture content. Size analysis of the samples was performed using both manual and mechanical screens. The dried refuse was placed on the largest of the manually held screens and shaken until no further refuse was observed to pass through the screen. The oversize from the screen was collected and weighed, and the undersize was placed on the next smaller screen. The process was then repeated until all four manual screens had been used.

The undersize from the 2.54 centimeter manually held screen was next processed through the SWECO screens. Since the total mass of material in each sample was much larger than could be accommodated by any individual SWECO screen at one time, two screens were placed on the vibrating base simultaneously, and a series of small batches were fed to the screens until the entire sample was processed. After each small batch was screened for 15 minutes, the oversize on the screens was collected, the next batch of refuse placed on the screens and the process repeated until the entire sample had been processed. The total mass of screen oversize for each of the two screens was weighed and tabulated before processing through the next two pair of screens in the same manner. Finally the undersize from the 0.13 centimeter screen was collected, weighed, and tabulated along with the rest of the data.

SECTION 5

EXPERIMENTAL PROCEDURES

GENERAL PROCEDURES FOR POWER-FLOW RATE DATA COLLECTION

Installation of the potential and current transformers was done at each site by qualified electricians and connected to the power monitoring equipment under the direction of Cal Recovery personnel. After installation, the system was tested to insure all the connections were correct and nothing had been damaged during shipment. On actual days of testing, all the monitoring equipment was turned on and allowed to warm up for at least half an hour before data was collected. Several times during each day of testing, freewheeling power measurements were taken, including one which was obtained shortly after shredder startup with the rest obtained as shredding operations permitted throughout the day. Freewheeling power is defined as the power required to maintain constant rotational velocity of the shredder rotor under a no-load condition (i.e. during idling).

Flow rate samples and power level data were collected under a number of different operating conditions for the purpose of characterizing the shredders. To guarantee that the flow rate sample coincided exactly with the interval during which the power was monitored, it was necessary to accurately determine both the distance from the center line of the shredder discharge to the center line of the segment of the discharge conveyor from which the flow rate sample was gathered and the speed of the discharge conveyor itself. With the shredder sampling distance and conveyor speed known, it was generally possible to calculate the elapsed time needed for the sample to travel from the shredder to the point of sample collection from

$$t = \frac{d_1}{V} + \frac{2h^{1/2}}{g} \tag{3}$$

where: t = elapsed time (sec);
d_1 = shredder center line to sample center line distance (m);
V = speed of the conveyor from which the flow rate sample was collected (m/sec);
h = distance from the bottom of the grates at the center line of the shredder to the top of the discharge conveyor; and
g = acceleration due to gravity (m/sec^2).

The term $2\,h^{1/2}/g$ in equation 3 is used to take into account the time required for shredded material to drop from the grates of the shredder to the conveyor belt.

When the actual power-flow rate test was being done, the time at which the discharge conveyor stopped was marked on the chart and a value for the elapsed time was calculated. The point on the chart recording of the power level corresponding to the time during which the flow rate sample was just emerging from the shredder was found by measuring the distance, d, from the mark identifying when the discharge conveyor was stopped. A value for d was found from

$$d = V_c t \tag{4}$$

where: d = distance from discharge conveyor stop mark on the chart recording to the center of the chart interval during which the flow rate sample was emerging from the shredder (m);
V_c = chart recorder speed (m/sec); and
t = elapsed time (sec).

The complete interval on the chart recording during which the flow rate sample was being discharged was identified by measuring the distance $\pm \Delta$ from the point marking the center of the sample interval. A value for Δ is obtained from

$$\Delta = \frac{1}{2} \frac{L}{V} V_c \tag{5}$$

where: L = length of the conveyor segment from which the flow rate sample was collected (m);
V = speed of the conveyor from which the flow rate sample was collected (m/sec); and
V_c = chart recorder speed (m/sec).

The mass flow rate through the shredder was calculated from

$$\dot{m}_w = 3.6 \frac{MV}{L} \tag{6}$$

where: $\dot{m}_w$ = mass flow rate (T_wPH);
M = mass of the total sample removed from the discharge conveyor (kg); and
L = length of the conveyor segment from which the flow rate sample was collected (m); and
V = speed of the conveyor from which the flow rate sample was collected (m/sec).

Preparation of the refuse samples for shipment included bagging and weighing the samples. The bagged samples were tagged with the date, weight, and sample number, placed in a second plastic bag to insure against puncture damage to the inner bag, and packed into shipping containers for transport to CRS for size and moisture analysis.

In order to ensure that a representative sample for the size distribution analysis was obtained, the sample size was varied according to the grate spacing of the shredder undergoing testing. In general, the larger the grate spacing, the larger the sample that needed to be gathered. The reason for the selection of this method for determination of sample size follows from the fact that, in general, relatively large particles issue from grates with large openings. Consequently in order to assure a sufficient number of particles for determination of the particle size spectrum, a large particle size dictates a large sample size.

An estimation of the sample size was made from Table 9:

TABLE 9. SAMPLE SIZE

Grate Spacing		Sample Size	
cm	(inches)	kg	(pounds)
20	(7.9)	10	(22.1)
15	(5.9)	7.5	(16.5)
10	(3.9)	5	(11.0)
5	(2.0)	2.5	(5.5)

The actual sample used for the size distribution and moisture analysis was obtained by thoroughly mixing the flow rate sample and dividing it into equal portions of the correct size. One of the portions so obtained was then prepared and shipped for subsequent size distribution and moisture analysis.

APPLETON PROCEDURE

Since both shredders at Appleton use the same discharge conveyor, only one shredder at a time was fed refuse during the tests. In addition, the water spray used to control dust inside the shredders was turned off several minutes before all but the first test.

The motor control room in Appleton is located directly underneath the main control room. The person monitoring the power requirement of the shredder under test stood at the entrance to the motor control room in sight of the monitoring equipment. An operator was in the main control room, while another member of the testing team was stationed at the end of the horizontal discharge conveyor. After recording an interval of relatively constant power the person monitoring the power signaled both visually and audibly to the operator in the control room and marked the time of the signal on the chart recording. Upon receiving the signal, the control room operator stopped both the feed and discharge conveyors and allowed the shredder to empty. While the shredder was emptying, the final five meters of refuse on the discharge conveyor was collected and weighed in order to obtain flow rate data. Correlation of the flow rate and power data was accomplished through utilization of the methods outlined under General Procedures.

After collecting the flow rate sample, the discharge conveyor was advanced so the shredder holdup (the mass of material actually within the shredder at the instant the feed conveyor was stopped) could also be collected and weighed.

AMES PROCEDURE

The motor control room at the Ames facility is also located directly under the main control room, and a telephone intercom system connects the two control rooms. Because the shredders operate in series, somewhat different techniques from those used at Appleton were utilized for collecting the necessary data for each shredder. The presence of vibratory discharge conveyors with no readily measurable transport speed made it impossible to use equation 3 to determine the elapsed time needed for a particle of refuse to travel from the center line of the shredder to the center line of the conveyor segment from which the flow rate sample was to be collected. Instead the elapsed times were determined by measuring the travel time of refuse samples with a digital chronometer as the refuse was transported along the conveyors from the shredders to the respective sampling stations. The sampling station for the primary shredder was approximately at the midpoint of the inclined conveyor which feeds the secondary shredder, while the secondary shredder sampling station was in the surge bin at the end of the second inclined discharge conveyor.

To obtain a sample for the primary shredder, the magnetic belt over the discharge conveyor was turned off and one of the test personnel began to monitor the power level. After recording a period of relatively constant power, the operator in the main control room was signaled over the intercom to stop the feed and discharge conveyors serving the primary shredder. The time at which the conveyors were stopped was noted on the chart recording. Three meters of inclined conveyor were swept clean of refuse, and the refuse sample thus collected was weighed and the entire sample prepared for shipment. Since both the belt speed and the time of travel between the shredder and sample were known, the flow rate determination and sample correlation with power requirements were done as described in the section on General Procedures with the exception that the elapsed time required for refuse to travel from the shredder to the sampling station was measured directly rather than calculated.

Sampling the secondary shredder in the same manner as the primary shredder would have hindered plant operation (due to material accummulation between the shredder grates and the vibratory discharge conveyor), so an alternative sampling method was developed. A large box was constructed and suspended inside the air classifier surge bin such that, when pulled into a retracted position by ropes affixed to the corners of the box, the box was held clear of the refuse stream; yet when the ropes were released, the box would swing forward and catch the entire flow of refuse for as long as necessary to fill the box. Since it was no longer necessary to halt any of the equipment in order to obtain samples using such a technique, plant operation was not affected by secondary sample collection.

The exact procedure used to obtain flow rate and power data for the secondary shredder was as follows:

1. A period of relatively constant power was recorded on the chart recorder.
2. The sample box was swung into position and the digital chronometer started in the Split/Cumulative mode (see Other Equipment for a discussion of the Split/Cumulative mode).
3. When the sample box was full, it was removed from the refuse stream and the digital chronometer was stopped.
4. The sample box was removed from the surge bin.
5. The member of the testing team with the chronometer returned to the power monitoring equipment and wrote the time displayed by the chronometer (in this case, the time needed to fill the box) on the chart recording without stopping the chart.
6. Next, the master control button on the chronometer was pressed again while simultaneously removing the pen from the chart paper.
7. The chart recorder was stopped and the new number displayed by the chronometer was written on the chart. The final number displayed represented the total time elapsed since the sample box was swung into position.

The period during which the sample was emerging from the shredder could be located on the chart recording by measuring the distance d $\pm$ Δ from the chart recording when d is found from

$$d = V_c \left(t_2 + t_3 - \frac{t_1}{2}\right) \qquad (7)$$

where: V_c = the chart recorder speed (m/sec);
t_1 = the amount of time needed to fill the sample box (sec);
t_2 = the elapsed time between swinging the box into position and removing the pen from the chart paper (sec); and
t_3 = the amount of time needed for particles of refuse to travel from the shredder to the surge bin (sec).

and Δ is found from

$$\Delta = \frac{1}{2}(V_c t_1) \qquad (8)$$

The sample of shredded refuse that was collected in the box was weighed, and a two to five kilogram subsample was prepared for shipment to CRS for further analysis.

The flow rate for the secondary shredder was calculated from

$$\dot{m}_w = 3.6\frac{M}{t_1} \tag{9}$$

where: m_w = flow rate (T_wPH);
M = total sample mass (kg); and
t_1 = time necessary to fill the box (sec).

COCKEYSVILLE PROCEDURE

The Cockeysville facility has separate motor and main control rooms for each shredder with neither intercom nor line-of-sight communication existing between the motor and main control rooms of either shredder. Therefore, short-range radios were used for communication between the test and operating personnel. Since the shredder motors at the Cockeysville facility are reversible and the shredders are run in both forward and reverse directions on an alternating day basis, data was collected for both directions of motor rotation.

To obtain a sample of shredded refuse, one of the test personnel signaled the shredder operator to stop the feed and discharge conveyor after an interval of relatively constant power was recorded. At the same time a reference mark noting the point at which the conveyors stopped was made on the chart recording. After stopping the conveyors, a three-meter segment of conveyor located at approximately the mid-point of the inclined rubber belt conveyor was swept clean of refuse and weighed. From the collected material, a representative sample of 8-13 kilograms was gathered and prepared for shipment to Richmond, CA, for further analysis.

Since the Cockeysville shredders discharge onto short discharge conveyors which, in turn, empty onto the long inclined conveyors from which the flow rate samples were collected, it was necessary to modify equation 3 in order to correctly determine the time needed for refuse to travel from the shredder to the point of sample collection. Equation 3, as modified for the Cockeysville calculations, becomes

$$t = \frac{d_1}{V_1} + \frac{d_2}{V_2} + {\frac{2h_1}{g}}^{1/2} + {\frac{2h_2}{g}}^{1/2} \tag{10}$$

where: d_1 = horizontal distance from the shredder center line to the point below which the refuse stream impacted upon the inclined conveyor (m);
V_1 = velocity of the discharge conveyor (m/sec);
d_2 = distance from the point at which the refuse stream impacted on the inclined conveyor to the center line of the segment from which the flow rate sample was taken (m);
V_2 = the velocity of the inclined conveyor (m/sec).

h_1 = vertical distance from the bottom of the grates at the center line of the shredder to the top of the horizontal discharge conveyor;
h_2 = vertical distance between the top of the discharge conveyor and the point at which the refuse stream impacted upon the inclined conveyor (m); and
g = acceleration due to gravity (m/sec);

With the use of equation 10 instead of equation 3, flow rate determination and correlation with power requirements were done as described under General Procedures.

GREAT FALLS PROCEDURE

Both shredders at Great Falls discharge onto a common conveyor, so feed to the shredder which was not being tested was stopped and sufficient time allowed for the untested shredder to empty before starting the test.

Since the power monitoring equipment was installed in a location from which observation of the rest of the plant was impossible, the method for obtaining data as described under General Procedures was modified slightly to better suit the circumstances. The distance from the center line of the shredder discharge to the center line of the segment of conveyor from which the sample was obtained was carefully measured as were the velocity of the horizontal and inclined discharge conveyors. From the distance and velocity data the time, t, needed for refuse to travel from the shredder to the sample point could be calculated from

$$t = \frac{d_1}{V_1} + \frac{d_2}{V_2} + {\frac{2h_1}{g}}^{1/2} + {\frac{2h_2}{g}}^{1/2} \qquad (10)$$

where: d_1 = horizontal distance from the shredder discharge center line to the point below which the refuse stream impacted upon the inclined conveyor (m);
V_1 = velocity of the horizontal discharge conveyor (m/sec);
d_2 = distance from the point at which the refuse stream impacted upon the inclined conveyor to the center line of the segment from which the flow rate sample was taken (m);
V_2 = velocity of the inclined discharge conveyor (m/sec);
h_1 = vertical distance from the midpoint of the shredder discharge opening to the top of the horizontal discharge conveyor;
h_2 = vertical distance between the top of the horizontal discharge conveyor and the point at which the refuse stream impacted upon the inclined conveyor; and
g = acceleration due to gravity (m/sec^2).

At the beginning of each experiment a member of the test team started the monitoring equipment and, after returning to the control room to stand with one of the plant operators, started the chronometer. Approximately t seconds later the operator was told to stop both the feed and discharge belts. Since the feed and discharge belts are interlocked, a single control button was able to stop them both simultaneously. With the chronometer still accumulating time, the test team member returned to the location of the monitoring equipment and stopped the chronometer simultaneously with removing the pen from the chart paper. The total elapsed time, t_t, displayed by the chronometer was then recorded.

The midpoint of the section of chart paper corresponding to the midpoint of the flow rate sample was located by measuring the distance, d, from the end of the inked line on the chart. The value of d was found from

$$d = (t_t - t)V_c \tag{11}$$

where: t_t = total elapsed time (sec);
t = time for refuse to travel from shredder midpoint to sampling midpoint (sec);
and
V_c = velocity of the chart (m/sec).

Determination of the complete interval on the chart recording during which the flow rate sample was being discharged, calculation of flow rate, correlation of power and flow rate, and sample shipment were performed as described in General Procedures.

TINTON FALLS PROCEDURE

The tipping floor is the only part of the Tinton Falls facility which is common to both shredders. However, the layouts of the two shredding lines are virtually identical, so the same testing procedure could be used on either line. A three meter section near the end of the discharge conveyor belt was selected as the most convenient point at which to obtain flow rate samples. The ferrous recovery magnets were turned off before running any tests so the entire flow rate could be measured.

Prior to testing, the distance from the shredder discharge to the center line of the sampling segment and the discharge conveyor belt speed were carefully measured. The speed and distance data were used in conjunction with equation 3 to obtain a value for t, the time needed for refuse to travel from the shredder to the midpoint of the sampling segment. Due to the design of the shredder, the value of h in equation 3 is zero. For each test, the monitoring equipment was started and allowed to record the power level for at least one minute before the conveyors were stopped.

The power monitoring equipment was located in the transfer trailer compactor room near the controls for the discharge conveyor and the location selected for obtaining flow rate samples. Since the shredder and the feed conveyor are controlled from the main control room which cannot be seen from the compactor room, coordination between the operator in the control room and test personnel in the compactor room was affected through an intercom system. If the discharge conveyor had been stopped at the same time as the feed conveyor, jams in the shredder discharge could have resulted. By waiting approximately t seconds (the length of time necessary for refuse to travel from the shredder discharge to the center of the sampling area) ample time was provided for the shredder to empty and thus avoid discharge jams. The operator in the control room was told when to stop the feed conveyor. Simultaneously the chronometer was started. Roughly t seconds after the feed conveyor was stopped, one of the test personnel simultaneously stopped both the discharge conveyor and the chronometer before returning to the monitoring equipment. The time, t_1, displayed by the chronometer was recorded on the chart itself and the Start/Stop switch on the chronometer activated a second time simultaneously with removal of the pen from the chart. Since the chronometer was operating in the Split/Cumulative mode (see Other Equipment for details) the time, t_t, displayed by the chronometer after the second activation of the Start/Stop switch was the total time accumulated since the chronometer was initially started. The value of t_t was also recorded, and all the refuse was removed from the three meter section of the conveyor which had been selected for flow rate sampling. The refuse was weighed, and a representative subsample was removed and prepared for shipment as discussed under General Procedures.

Measurement of the distance, d, from the end of the inked line on the chart located the midpoint of the section of chartpaper which corresponded to the midpoint of the flow rate sample.The distance, d, was calculated from

$$d = (t_t - t_1 + t)V_c \tag{12}$$

where: t_t = total elapsed time between stopping the feed conveyor and removing the pen from the chart (sec);
t_1 = elapsed time between stopping the feed and discharge conveyors;
t = time required for sample to travel from discharge to centerline of sample (sec); and
V_c = chart speed (m/sec)

Again, determination of the complete interval on the chart during which the flow rate sample was being discharged, calculation of flow rate, and correlation of power and flow rate were performed as described in General Procedures.

ODESSA PROCEDURE

A 2.4 meter section of belt just above the point at which the discharge conveyor reached ground level was selected as the best flow rate sampling area. The belt speed and distance from the centerline of the sampling area to the centerline of the shredder were carefully measured and used in conjunction with equation 3 to obtain a value for the time, t, needed for refuse to travel from the shredder to the midpoint of the sampling area.

The power monitoring equipment was placed in the motor control room (located under the feed conveyor and just behind the shredder discharge). Due to the potential danger of falling objects and explosions, personnel were not permitted in the shredder pit while refuse was being fed to the shredder, thus limiting the opportunities for sampling to those times when a full transfer trailer was being replaced by an empty one. Although the shredder at the Odessa plant is reversible, all the sampling was done when the shredder was running in the forward direction. The chart recorder was started as the full transfer trailer was being removed. The hydraulic push pit into which shredded refuse was discharged had enough capacity to hold roughly the amount of refuse which could be shredded in five minutes of normal operation. The feed conveyor was restarted and refuse fed to the shredder until the shredder motor current monitor in the control room indicated a relatively constant load. The feed conveyor was then halted and the chronometer simultaneously started. Allowing some time between stopping the discharge conveyor reduced the possibility of jamming the shredder discharge. Approximately t seconds after stopping the feed conveyor, the discharge conveyor was also stopped and the elapsed time, t, between stopping the two conveyors was recorded. A reference mark on the chart was obtained by removing the pen from the paper. The total elapsed time, t_t, from stopping the feed conveyor to removing the pen from the chart paper was also recorded. The point on the chart corresponding to the flow rate sample was located by measuring a distance, d, from the point at which the pen was removed. The distance, d, was calculated through use of equation 12. Flow rate determination, location of the complete sample interval on the chart, and power-flow rate correlation were performed as described in General Procedures.

HAMMER WEAR EXPERIMENTAL PROCEDURE

General Procedure

Hammer wear investigations were conducted on base hammer materials as well as on a number of hardfacing alloys. The experimental procedure consisted of cleaning and weighing hammers prior and subsequent to shredding a measured amount of solid waste. The quantity of hammer material lost and tonnage of refuse shredded were used to ascertain the degree of wear (W_0) for each type of hammer base material or hardfacing alloy tested. As is common in the industry, the degree of wear is expressed as the weight of material lost due to wear per unit weight of refuse shredded.

Hammer wear tests were conducted by CRS for each site except Ames, Tinton Falls, and Odessa. Since hammer retipping is not practiced at Ames, Tinton Falls, or Odessa, wear data for these sites were provided by the plant operators. Tonnage for all the wear experiments were monitored by the truck scales located at each facility. A general overview of the wear experiments conducted at each site is provided in the following paragraphs.

Appleton

Two sets of hammer wear data were collected at the Appleton facility. One data set involved hammer wear in the east mill where 12 hammers hardfaced with two passes of Stoody 134 electrode were cleaned, weighed, and placed in the mill in two rows of six hammers each. After shredding 398 tons of waste, the east mill hammers were removed, cleaned, and reweighed.

The other data set was obtained from the west mill. Each of the four rows of 12 hammers in the west mill was hardfaced with two passes of hardfacing alloy. The four alloys tested were McKay 48, McKay 40 TiC, Stoody

134, and Amsco Super 20. Hammers were cleaned, weighed, and installed after the hardfacing was applied (Figure 33). In order to facilitate proper identification of test alloys, each row of hammers containing a particular application of hardfacing alloy was marked in the shredder and noted on the data sheets. After shredding 141 tons, the hammers were removed, cleaned and reweighed.

Hammers used in both mills were built-up prior to hardfacing application with Stoody 110 electrode.

Ames

The wear data for the Ames site was supplied by the city of Ames. The data covered hammer wear for the primary shredder over the four-month period from October 11, 1977, to February 11, 1978. Since the hammers in the primary shredder were neither hardfaced nor built-up, these data give the wear of the base hammer material (manganese steel). Each of four rows of 12 new hammers was weighed and installed in October. After four months of operation in which 14,254 tons of waste were shredded, each row of hammers was pulled and reweighed. The hammer weight and tonnage information was subsequently transmitted by letter to CRS by the city of Ames.

Cockeysville

Two sets of hammer wear data were collected at the Baltimore County facility. The first set consisted of wear determination of manganese steel hammers installed in shredder #2. These hammers were installed new and without any deposition of hardfacing or build-up material. Hammers were cleaned and weighed prior to installation. After shredding 305 tons of waste, these hammers were removed, cleaned, and reweighed.

The second set of wear experiments were conducted using the same hammers which were worn-in during the first data set and subsequently built-up with McKay 118 electrode before application of the hardfacing alloys. Each of the four rows of hammers (six hammers per row) was coated with one pass of a hardfacing alloy. The four alloys tested were: 1) Lincoln Mangjet, 2) Lincoln Abrasoweld, 3) McKay 55, and 4) Lincoln Faceweld 12. After application of the hardfacing alloys, the hammers were cleaned, weighed, and installed in shredder #1 (Figure 34). So the test alloys could be identified, each row of hammers containing a particular application of hardfacing material was marked in the shredder and noted on the data sheets. After shredding 255 tons of waste, the hammers were removed, cleaned, and reweighed.

Great Falls

Hammer wear data was obtained from the Model 42F shredder at the Great Falls facility. The 42F vertical shaft hammermill has three distinct zones within the shredder (Figure 35). The top zone, in which refuse undergoes preliminary breakage, is known as the breakage zone and extends from the top of the shredder to the bottom of the section with the cone-shaped walls. There were 20 hammers in the breakage zone. The middle or grinding zone

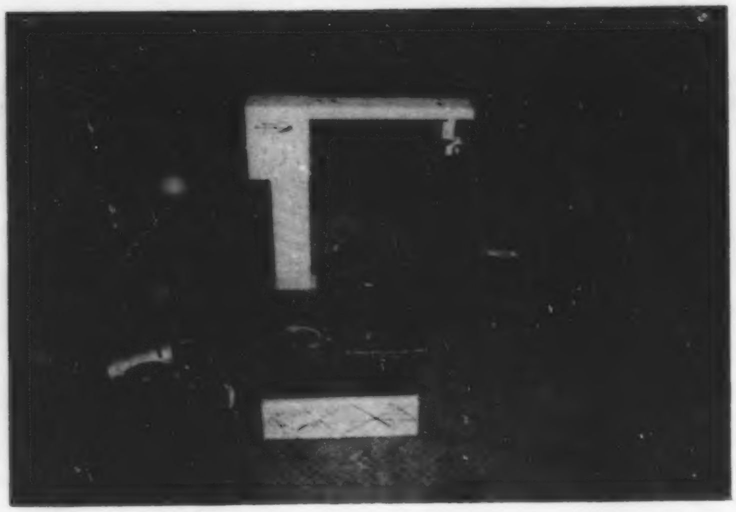


Figure 33. Cleaned hammer being weighed prior to installation in west mill.

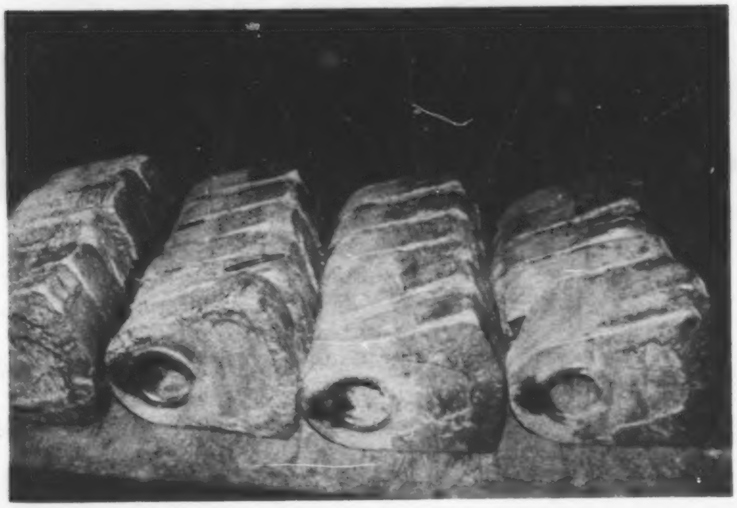


Figure 34. Set of newly hardfaced hammers ready for installation at the Cockeysville facility (note pen resting on hammer for reference of scale).

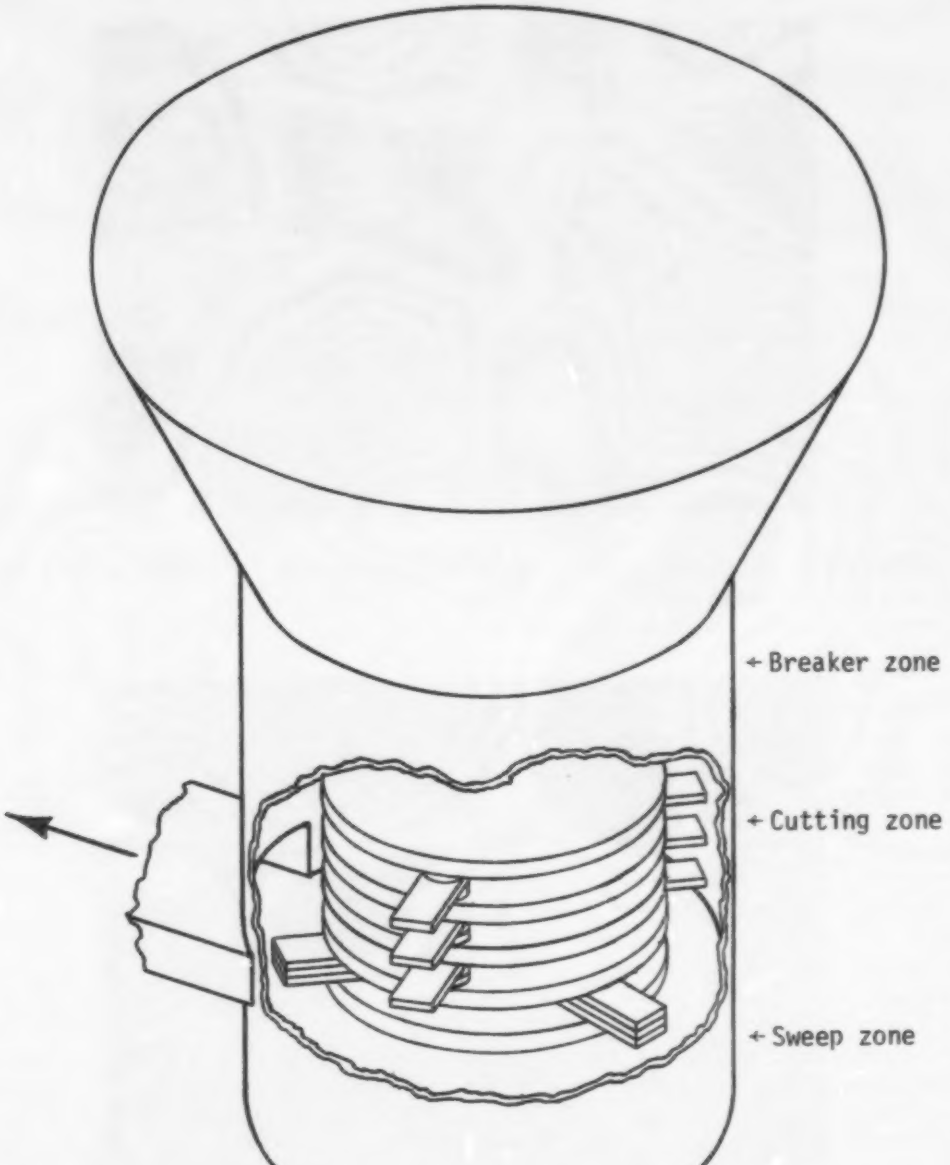

← Breaker zone
← Cutting zone
← Sweep zone

Figure 35. Pictoral of vertical hammermill.

contains nine hammers and, as the name implies, is where most of the shredding takes place. The bottom area is the exit zone in which shredded refuse is forced from the shredder by a series of nine hammers arranged in three groups of three hammers each. The hammers in the three zones are known as breakers, cutters, and sweeps respectively.

Twenty-six new hammers were used in the wear tests. Nine hammers were hardfaced with Stoody 2134, nine with Amsco Super 20, and eight were left bare. All twenty-six hammers were cleaned and weighed prior to installation. The first group of sweeps was replaced with three Amsco surfaced hammers, the second with three Stoody surfaced hammers, and the third with three bare hammers. Each vertical row of cutters was similarly replaced so that the wear of the different surfaces could be compared for the same height above the bottom of the shredder. Only the lower eight of the breakers were replaced with new hammers since the upper breakers experience very little wear. After shredding 126.9 tons, the hammers were reversed so as to present the opposite face to the refuse and, after shredding an additional 51.4 tons, were removed, cleaned, and reweighed.

Tinton Falls

The wear data for the Tinton Falls facility was provided by the plant manager. The data represented grinder wear for the period from October, 1978, through January, 1979, during which 16,353 tons of refuse were shredded. The ring grinders were never resurfaced so the data represents the wear of the base grinder material, in this case nickel-manganese steel. The Tinton Falls shredders utilize 60 grinders in 5 flights of 12 grinders each. After shredding 16,353 tons of refuse, the grinders were removed, cleaned, and weighed. The tonnage shredded and the initial and final weights were then sent to CRS for analysis. The internal configuration of the ring shredder showing the locations of the ring grinders is presented in Figure 36.

Odessa

Wear data for the Odessa site was provided by the Sanitation Department of the City of Odessa. The data were collected during the winter of 1978 during which 5,201 tons of refuse were shredded. Again, since hammer retipping is not practiced at this site the wear data represents the wear of the base material. The 14 new hammers (in rows of four, three, four and three hammers each) were weighed and the weights recorded before installation. When the hammers were removed, they were weighed a second time and the weights again recorded. The initial and final weights and the total tonnage shredded were turned over to CRS for analysis.

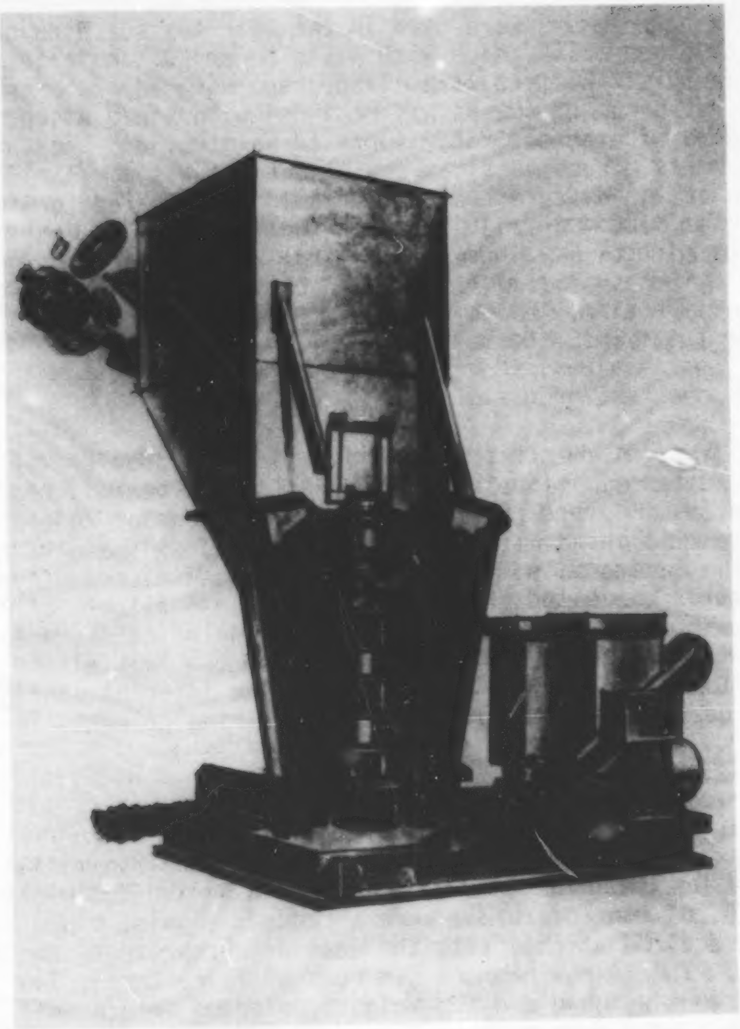


Figure 36. Internal configuration of the Tinton Falls ring shredder.

SECTION 6

RESULTS AND DISCUSSION

MOISTURE CONTENT OF SHREDDED REFUSE SAMPLES

Average air dry moisture contents of the shredded refuse samples exhibited a range of approximately 16 to 36 percent (Table 10).[a] The Appleton refuse had the highest moisture content, averaging in the neighborhood of 30 to 36 percent. Although a water spray is sometimes used at Appleton to control dust dispersion, the spray was turned off five minutes before beginning the test runs. Consequently the moisture contents for Appleton are average innate values. None of the other sites used a water spray system during the test programs.

The average moisture contents of shredded refuse at the other five sites tended to be rather low, (in the range of 16 to 22 percent) when compared to "typical" refuse. A range of 25 to 30 percent air dry moisture content is typical of shredded refuse. The primary reason for the low values is the time period of the tests, namely late fall and winter. A lack of green lawn and garden debris exhibited during this time period accounts for the relatively low moisture contents. Appleton on the other hand was tested during September when significant quantitites of green lawn and garden debris were present in the refuse brought to the plant.

Based upon visual observation, the refuse processed at the Ames and Cockeysville plants was characterized as "commercial" waste, that is waste tending to have a large particle size and significant quantities of paper and plastic. Refuse at the other four sites was characterized as "residential". Such waste contains lawn and garden debris, food waste, and tends to contain particles that are smaller than those typical of commercial waste.

MEASURED THROUGHPUTS

The primary purpose of this study was to obtain performance and operating data on large-scale shredders, that is, shredders capable of handling large throughputs of solid waste. Shredders evaluated in this study covered the full spectrum of throughput capacity ranging from an average of approximately 20 TPH at the Ames plant to 82 TPH at the Odessa facility (wet weight basis). The minimum throughput measured during the tests was 3.5 TPH at the Appleton facility while the maximum throughput was 127.4 TPH measured at the

---

[a] For shredded refuse, bone dry moisture content (percent) equals air dry moisture content (percent) plus 8 to 9 percent.

TABLE 10. SUMMARY OF AVERAGE VALUES OF IMPORTANT PARAMETERS MEASURED DURING THE SHREDDER PERFORMANCE EVALUATION

Shredder	MC (%)	Throughput $\bar{m}_w$ (TPH)	$\bar{m}_d$ (TPH)	Characteristic Size $\bar{X}_o$ (cm)	σ_o (cm)	Nominal Characteristic Size $\bar{X}_{90}$ (cm)	σ_{90} (cm)	Specific Energy $\bar{E}_o$ $\left[\frac{Kwh}{T_d}\right]$	σ_{E_o} $\left[\frac{Kwh}{T_d}\right]$	$\bar{E}_{o_w}$ $\left[\frac{Kwh}{T_w}\right]$	$\sigma_{E_{o_w}}$ $\left[\frac{Kwh}{T_w}\right]$	Notes#
Appleton East	35.6	27.0	17.1	3.8	1.0	9.9	1.0	4.6	2.5	3.0	1.9	a
Appleton East	35.0	24.8	18.1	3.7	0.9	9.8	1.0	4.7	2.6	3.4	1.7	b **
Appleton West	30.1	18.1	11.7	5.6	0.9	11.2	1.2	5.3	2.0	3.9	2.0	e,h
Ames Primary	15.9	19.6	16.5	4.6	1.5	11.7	3.5	6.1	3.2	5.1	2.6	e
Ames Primary	16.3	18.6	15.6	5.0	0.9	12.1	3.5	6.6	3.0	5.5	2.4	c **
Ames Secondary	21.8	20.9	16.3	1.4	0.2	3.4	0.6	13.1	6.3	9.9	4.1	e
Ames Secondary	22.2	22.4	17.4	1.3	0.2	3.3	0.5	14.2	5.5	10.8	3.3	d **
Cockeysville												
Shredder #1 (F)	16.3	39.3	32.9	2.2	0.5	6.4	1.3	12.9	2.6	10.8	2.4	e,f **
Shredder #1 (R)	17.9	59.8	48.9	2.0	0.3	6.1	1.0	11.0	1.6	9.1	1.8	e,g **
Combined #1	17.1	49.5	41.1	2.1	0.4	6.2	1.2	11.9	2.4	10.0	2.4	e
Great Falls 20TPH	21.1	14.8	11.5	2.4	0.8	5.6	1.7	8.2	2.5	6.4	2.0	e **
Tinton Falls	19.2	60.8	48.6	3.8	0.8	9.6	1.8	2.8	0.7	2.3	0.6	e **
Odessa (F)	17.8	82.0	66.7	3.2	1.2	9.2	4.0	0.8	0.7	1.1	0.7	e,f **

Notes: (test numbers refer to tests listed for each site and shredder in Appendix A)

a Excludes test #3, which was aborted due to extreme water content
b Excludes tests #3 and #9; #9 was conducted at abnormally low flow rate and results are not indicative of normal operation
c Excludes test #10, which was largely dirt and demo debris; judged non-representative of normal waste
d Excludes test #5, which was conducted at an abnormally low flow rate
e all test runs included
f F = Forward Rotation (see text for explanation)
g R = Reverse Rotation (see text for explanation)
h 3 samples only to establish representative product size for wear experiments in West Mill
** Data used in report as representative of average operating conditions at each plant

Odessa plant, again on a wet weight basis. It must be pointed out that both of the above extreme values were special test runs and therefore are not indicative of normal plant operation.

Average values for throughputs that were measured at each plant, along with minimum and maximum values, are summarized in Table 11. Data are shown on both wet and dry weight bases. Scrutiny of the data in the table shows a wide spectrum of throughputs about the average value for each site. These wide variations are a consequence of obtaining performance and operational data over as wide a throughput base as plant operation would permit.

TABLE 11. THROUGHPUTS MEASURED DURING SHREDDER PERFORMANCE EVALUATIONS

Shredder	$\dot{m}_w$ (TPH)			$\dot{m}_d$ (TPH)		
	Min	Max	Avg	Min	Max	Avg
Appleton East	3.5	47.5	27.0	2.1	34.0	17.1
Ames Primary	10.6	35.1	19.6	8.3	28.6	16.5
Ames Secondary	7.0	27.2	20.9	5.7	22.2	16.3
Cockeysville #1 (F)[a]	22.6	52.3	39.3	18.8	43.7	32.9
Cockeysville #2 (R)[b]	39.4	95.7	59.8	34.6	81.9	48.9
Great Falls 20 TPH	10.0	19.4	14.8	8.1	15.3	11.5
Tinton Falls	20.7	99.5	60.8	17.2	76.5	48.6
Odessa (F)[a]	13.3	127.4	82.0	11.9	108.3	66.7

[a] F = forward rotation

[b] R = reverse rotation

SIZE DISTRIBUTION OF SHREDDED SOLID WASTE

In keeping with information available in the literature and the experience of CRS in developing relationships among the parameters governing the process of size reduction, the results of the size distribution analysis are reported chiefly in terms of characteristic size, i.e., the screen size corresponding to 63.2 percent cumulative passing. At the same time, the nominal product size, or that screen size corresponding to 90 percent cumulative passing, is accepted for use by the solid waste industry in general. Both size designations, where appropriate, are included for the reader's consideration. We must emphasize, however, that studies in size reduction of solid waste have shown that there is a greater degree of correlation between characteristic size and other variables of size reduction (most significantly specific energy) than exists between nominal size and other variables of size reduction.

As a matter of scientific interest and also as a means for developing a method of interchangeability between characteristic (X_o) and nominal (X^{90}) product sizes, a relation has been developed between these size parameters based upon average values of the data obtained from the test sites and University of California data. This relationship is presented in Figure 37 and can be expressed as,

$$\overline{X}_{90} = 2.23\, X_o + 0.69 \tag{13}$$

with a correlation coefficient of 0.93.

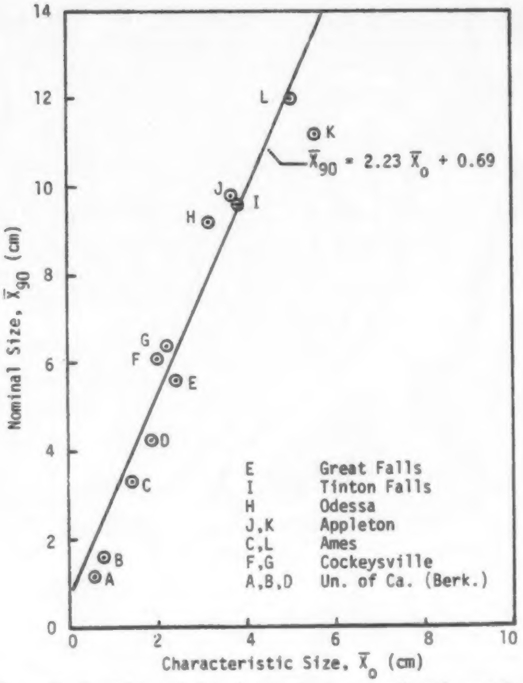


Figure 37. Relationship between nominal and characteristic product sizes for shredded MSW.

Average values of the characteristic and nominal sizes for shredded refuse samples collected at the test sites along with other pertinent shredding and operational parameters are shown in Table 10. The reader should witness the notes to the data since some of the average values include data which was not typical of normal plant operation. As part of the research, some tests were conducted at very low throughputs. These special tests and their results are discussed later. The data corresponding to normal plant operation are designated by (**) in the table. The data used to develop Table 10 are included in Appendix A.

Under typical operating conditions, the average values of characteristic product sizes varied from a maximum of 5.6 cm for the Appleton west mill to a minimum of 1.3 cm for the Ames secondary shredder while the average values of nominal product size ranged from a maximum of 12.1 cm from the Ames primary shredder to a minimum of 3.3 cm from the Ames secondary mill.

Reference should also be made to the average characteristic (nominal) sizes encountered at the Cockeysville facility, namely on the order of 2.1 (6.2) cm. These values are not far removed from the average product sizes of material discharged from the Ames secondary shredder. Despite the fact that the Ames facility uses primary and secondary shredding, the characteristic size of the product is only marginally smaller (approximately 38 percent) than the size of the product resulting from the single shredding at the Cockeysville plant. The reasons that the product sizes from each of these plants are comparable involves a combination of factors which will be explained and discussed after presentation of the rest of the experimental data.

Because of the number of variables that affect the degree of size reduction, there is, in general, a wide dispersion of data about the average value of product size as evidenced in some instances by the large values of the standard deviation. Consequently when talking about product sizes from a particular shredder, one must be aware that there can be considerable instantaneous variations in size of the product. The variables that contribute to this dispersion of product sizes include moisture content, composition and size of refuse, and flow rate of material through the shredder. The effect of variation of throughput upon product size will be covered in more detail later in this report.

As a means of visualization of the results of the size distribution analysis, the range of size distributions for several different sites is plotted in Figure 38 along with typical size ranges for residential and commercial solid waste[a]. The wide band of the size spectrum for each shredder (as alluded to earlier) is apparent from the figure. The average size distribution for shredded material encountered at each site under normal operating conditions is shown in Figure 39, again with representative size distributions for residential and commercial solid waste also shown. In order to avoid congestion, the curve for Tinton Falls has been omitted from Figure 39. The average curve for Tinton Falls lies between those for Odessa and Appleton.

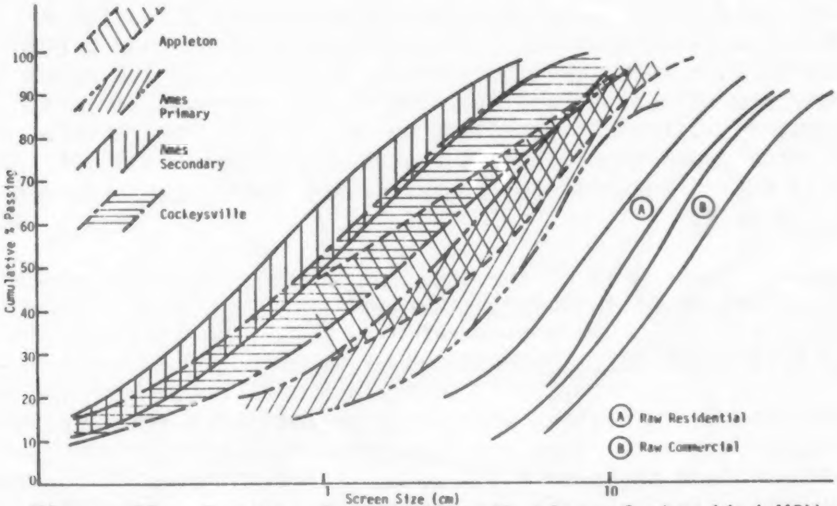


Figure 38. Ranges of size distribution of shredded MSW measured at Appleton, Ames, and Cockeysville

---

[a] The range of size distributions for raw residential and commercial solid waste were determined from University of California data and that resulting from studies conducted for private clients.

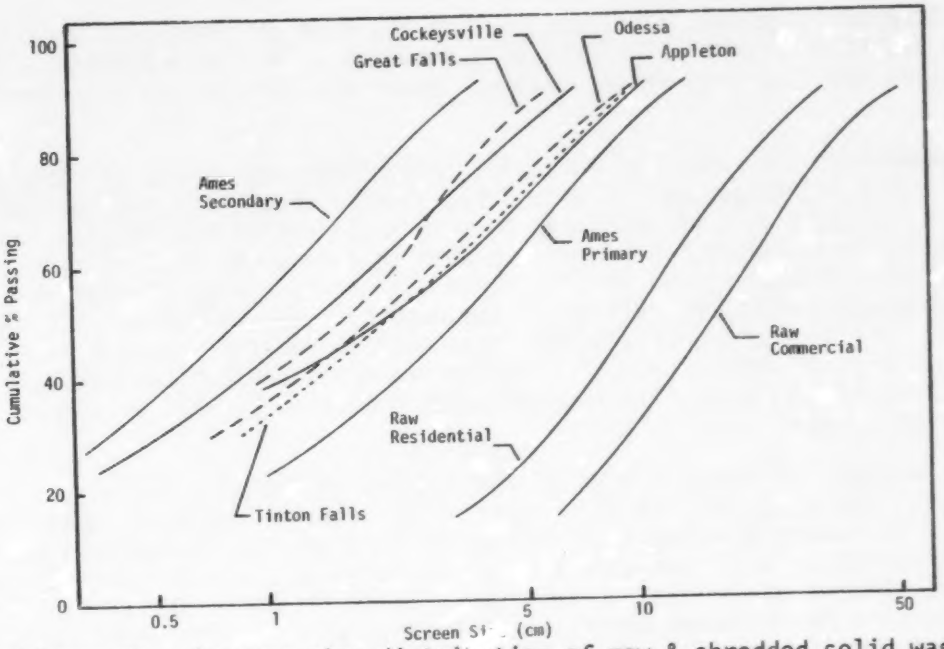


Figure 39. Average size distribution of raw & shredded solid waste

MEASURED POWER

Along with size, power is one of most important variables affected by throughput and moisture content. During the course of the study, power measurements were found to range from a minimum of 4.5 kw (Odessa) to a maximum of 957.8 kw (Cockeysville). The minimum, maximum, and average values encountered at each site are tabulated in Table 11. As indicated in Table 12, at least one data point was obtained at Cockeysville for which the net power momentarily exceeded the rating of the shredder drive motor. All the sites had motor protection circuits which would temporarily cut off the feed of refuse to the shredder if the motor current rating was exceeded for more than a few seconds.

The average power draw of the shredders that were tested ranged from 12.6 to 73.2 percent of full load motor rating.

THROUGHPUT EFFECTS ON SIZE

As some shredder operators are aware, product size tends to increase when a shredder is emptying or when the throughput to the mill is reduced significantly. Some tests were conducted at Appleton, Ames, and Tinton Falls to quantitatively verify the above observation. These tests included a run at each of the aforementioned sites in which the throughput to the shredder was significantly reduced below the average throughput value found under normal operating conditions. In each test, energy requirements and throughput were measured and the size distributions analyzed for later comparison with the data collected under normal operating conditions.

TABLE 12. POWER MEASURED DURING SHREDDER PERFORMANCE EVALUATION

	Net Power, P_n (kw) Min.	Max.	Average[c]	Full Load Motor Rating (kw)	Average as a % of Rating
Appleton East	7.8	167.3	76.0	298	25.5
Ames Primary	4.8	213.5	93.7	746	12.6
Ames Secondary	15.5	376.2	217.3	746	29.1
Cockeysville #1 (F)[a]	213.5	560.7	417.7	746	56.0
Cockeysville #1 (R)[b]	316.8	957.8	546.2	746	73.2
Great Falls 20TPH	32.8	128.3	92.4	187	49.4
Tinton Falls	61.5	281.5	134.9	746	18.1
Odessa (F)[a]	4.5	162.9	95.0	373	25.5

[a] F=Forward
[b] R=Reverse
[c] Average of all measurements taken at site

The experiments involving size reduction at low throughputs confirmed the observation of larger product size when compared to those average values encountered under regular operating conditions (Table 13). For example, at Appleton the average values for throughput (wet weight basis) and characteristic product size were 24.8 TPH and 3.7 cm, respectively, whereas data for a test at 3.5 TPH (wet weight basis) showed the product size to be 5.5 cm. Similarly, a test of the Ames secondary shredder at a low throughput of 7.0 TPH (wet weight basis) produced a characteristic product size of 1.7 cm while the product size under normal operating conditions, 22.4 TPH (wet weight basis), was 1.3 cm. The data collected at Tinton Falls exhibited the same trends as those shown for Appleton and Ames (Table 13).

The shift in product size due to the effects of variation of throughput is manifested in those tests conducted at low flow rates of refuse through the shredders. Other data (1), which were obtained under strict experimental procedures, are available that indicate product size is a function of throughput for a given set of operating conditions. Due to the concern for maintaining normal plant operation and the concomitant loss of rigid experimental control, it was not possible to develop reliable relationships between product size and throughput other than to substantiate that such a relationship does exist at the low end of throughput values.

As mentioned above, over the full range of throughput it was not possible to develop empirical relations for product size that were statistically significant. However, the data from four cases, namely the Ames primary and secondary shredders, the Odessa shredder, and the Tinton Falls shredder, are interesting from the standpoint of a potential avenue of further research. Although there is a good deal of scatter, plots of product size versus flow rate indicate a trend of decreased particle size for high flow rates, Figures 40, 41, 42, and 43. To substantiate these trends, a more comprehensive study of each shredder is needed and could be a topic for further research.

TABLE 13. EFFECT OF VARIATION OF THROUGHPUT UPON CHARACTERISTIC PRODUCT SIZE AND SPECIFIC ENERGY

Shredder	Shredder Operation	$\dot{m}_w$ (TPH)	$\dot{m}_d$ (TPH)	X_o (cm)	E_o Kwh/T_d
Appleton East	Average	24.8	18.1	3.7	4.7
Appleton East	Low Flow Rate	3.5	2.1	5.5	3.7
Ames Secondary	Average	22.4	17.4	1.3	14.2
Ames Secondary	Low Flow Rate	7.0	5.7	1.7	2.7
Tinton Falls	Average	60.8	49.1	3.8	2.8
Tinton Falls	Low Flow Rate	20.0	17.2	5.0	3.6

With regard to the data presented in Figures 40 through 43, it should be noted that the reduction of product size appears more noticeable for the X_o data as opposed to the X_{90} data. Data scatter also appears to be greater for the latter size data.

The resolution of the effects of throughput on size and energy consumption is important from the standpoint of control of the process of size reduction. For example, in a resource recovery facility incorporating shredding and recovering RDF, the particle size of the fuel will change somewhat for variations in the throughput to the shredders. If the particle size of the fuel is specified by the user, then a model or relationship between product size and throughput would allow the plant operator to establish the allowable variations in throughput values to maintain the recovered fuel within specification.

The argument can be expanded to include the input of shredded refuse into air classifiers, screens, and other processing equipment. These processing devices will obviously exhibit more efficient performance if they are provided with a uniform particle size. Establishment of the particle size consequently dictates the size range of the product discharged from the shredder, which in turn indicates the degree of variation in throughput that can be tolerated.

Although process control in resource recovery plants is now practiced to only a very limited degree, the successful and efficient operation of such facilities will eventually be dependent upon effective control of each unit process. Consequently, the development of a relationship between product size and refuse throughput is deemed as a necessary first step in the control of the size reduction process.

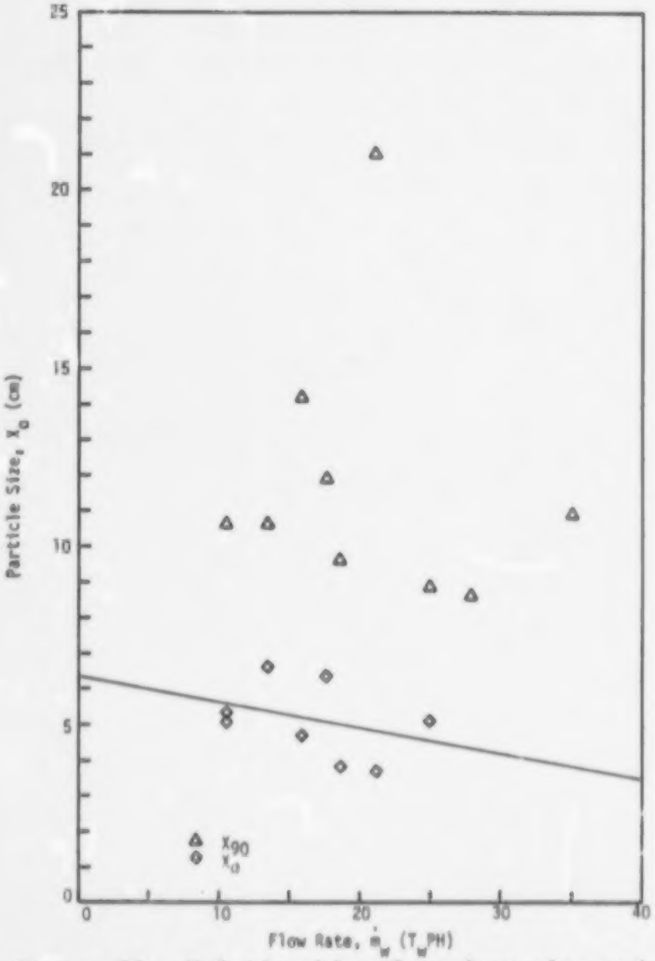


Figure 40. Relationship of product size and and throughput for Ames Primary Shredder.

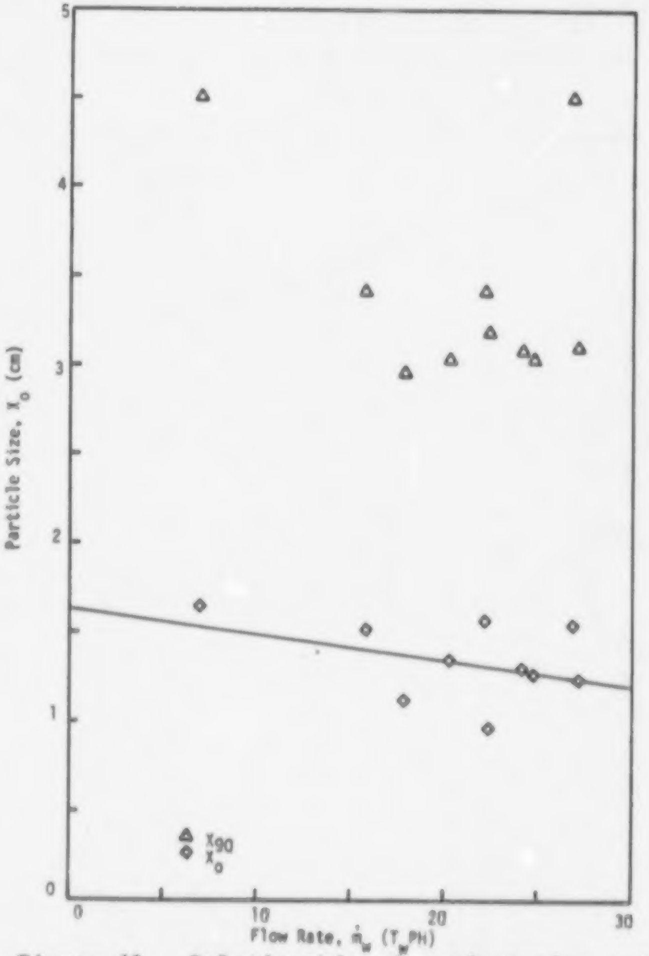


Figure 41. Relationship of product size and throughput for Ames Secondary Shredder.

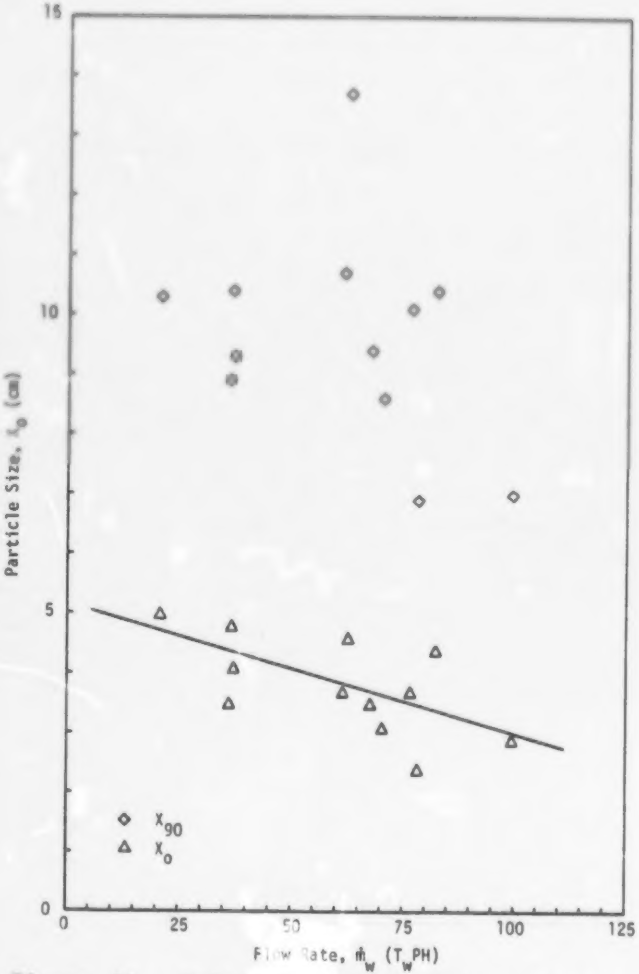


Figure 42. Relationship of product size and throughput for Tinton Falls shredder.

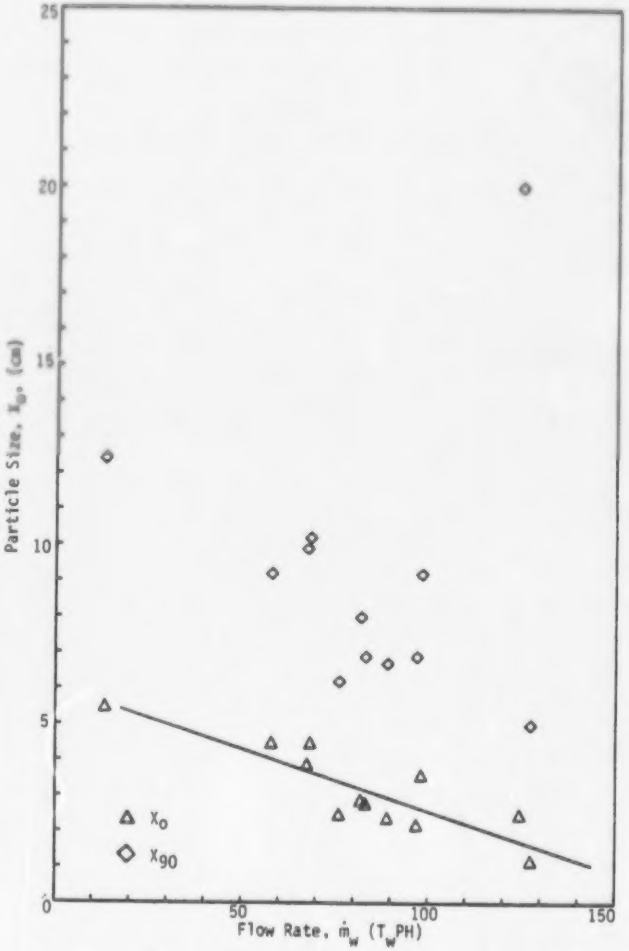


Figure 43. Relationship of product size and throughput for Odessa shredder.

ESTIMATION OF SPECIFIC ENERGY REQUIREMENTS

Data collected in the test program along with that from other sources (2) enables the development of relationships for the prediction of specific energy on a dry weight basis, E_o, (kwh/T_d), as functions of both characteristic and nominal product sizes (X_o and X_{90}, respectively) for horizontal hammermills. Average values of E_o, and X_o, and X_{90} and the range of one standard deviation for each variable are plotted in Figure 44. The trend of an increasing energy requirement as a consequence of producing smaller and smaller particle sizes through size reduction is quite apparent.

An attempt to develop a functional relationship between E_o and the size parameters using standard curve fitting techniques yielded the following equations:

$$E_o = 23.25\, X_o^{-0.92} \tag{14}$$

and

$$E_o = 49.94\, X_{90}^{-0.86} \tag{15}$$

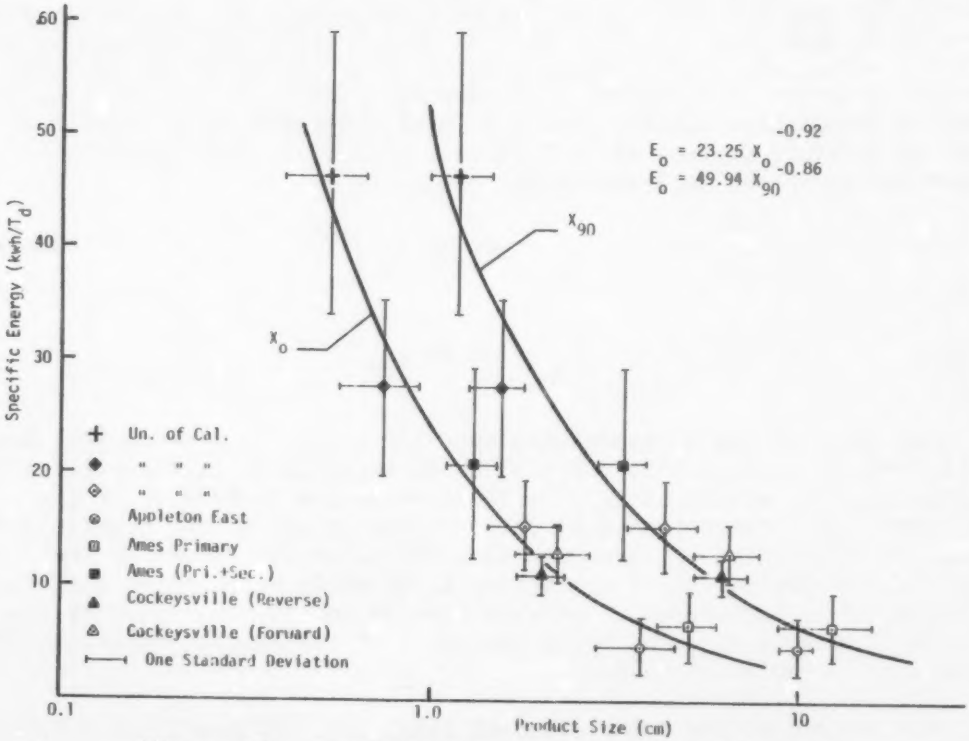


Figure 44. Specific energy consumption (A.D.B.) as a function of product size.

where E_0 is expressed in kwh/T_d and X_0 and X_{90} are expressed in cm. The correlation coefficients of equations 14 and 15 are 0.93 and 0.91 respectively.

Equations 14 and 15 indicate that specific energy on an air dry weight basis (A.D.B.) is approximately proportional to the -0.9 power of the characteristic size or nominal size.

These equations were developed with the aid of data from facilities handling anywhere from four to ninety tons of refuse per hour and consequently represent the full gamut of operating conditions found in actual practice. The curves should be valuable in estimating net power requirements for shredders in general. The term "in general" should not be overlooked since the actual power requirement for a particular shredder is a function of many variables including internal machine configuration, hammer tip speed, throughput, refuse size, composition, and moisture content. The dispersion bars about each average value in Figure 44 allow the range of specific energy that could be used as a consequence of producing a particle of a particular size to be estimated.

The preceding discussion was formulated on a dry weight basis, and consequently some estimation of moisture content is necessary before energy requirements can be calculated on a wet weight basis (W.B.). Although correlation between specific energy on a wet weight basis (kwh/T_w) and average product size is not as good as that between specific energy on an air dry weight basis and average product size, the relationship between the former variables is presented in Figure 45. The data represent samples ranging in moisture content from 6.9 to 47.5 percent (A.D.B.) with an average moisture content of 22.9 percent (A.D.B.). The appropriate governing equations on a wet weight basis are

$$E_{0_w} = 17.91\ X_0^{-0.90} \qquad (16)$$

$$E_{0_w} = 35.55\ X_{90}^{-0.81} \qquad (17)$$

Equations 16 and 17 expressing specific energy on a wet weight basis as a function of product size are similar to those calculated for specific energy on a dry weight basis. In addition to the similarity of the exponents, (all range from 0.81 to 0.92) the values of the constants for the equations containing X_{90} are approximately twice the values of the constants of the equations containing X_0 as would be expected when equation 13 is considered. For equations 14 and 15, the ratio of the leading constants is 2.15, while the ratio of the leading constants for equations 16 and 17 is 1.98.

With regard to the correlation of data, specific energy (A.D.B.) and average product size have correlation coefficients in the range of 0.91 to 0.93 while those for specific energy (W.B.) and average product size are in

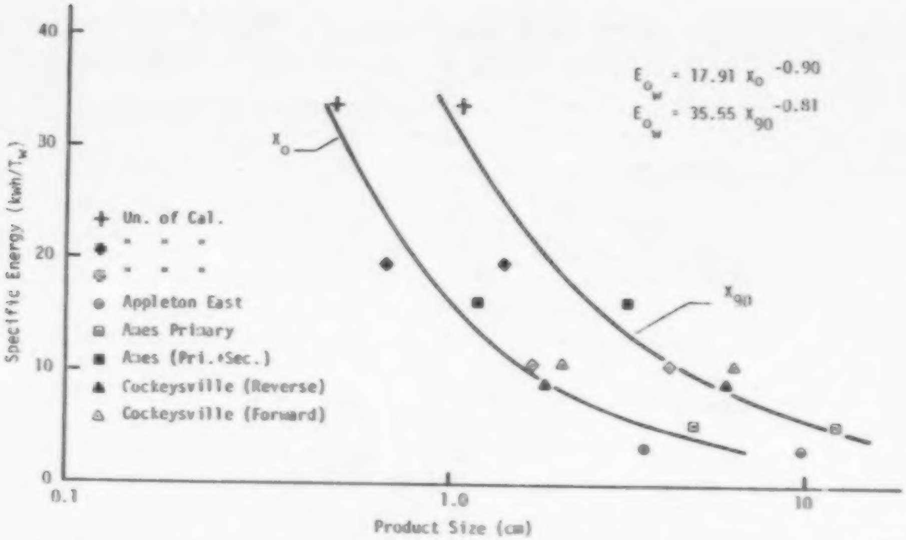


Figure 45. Specific energy consumption (W.B.) as a function of product size.

the range of 0.87 to 0.89. Consequently, correlation of product size with energy on an air dry weight basis is considered slightly more accurate.

The energy and size data for the vertical shredders located at Great Falls and Tinton Falls and the horizontal hammermill located in Odessa were not used to develop the relationships shown in Figures 44 and 45. The Great Falls and Tinton Falls test results were omitted because these data were for vertical, as opposed to horizontal, shredders. The Odessa test results were omitted because the data showed a lower specific energy consumption than would be predicted from the data collected from the other four horizontal hammermills and the University of California hammermill.

Statistical analysis of the data supports the conclusion that the vertical shredders and Odessa shredder need to be examined separately. An attempt to develop functional relationships predicated upon the results of all six test sites, i.e. both vertical and horizontal hammermills, results in correlation coefficients that are poorer than those developed solely for horizontal hammermill (Odessa data omitted). As previously discussed, correlation coefficients are approximately 0.9 for the curves developed for the horizontal hammermills whose test results are shown in Figures 44 and 45. On the other hand, if the test results for the vertical shredders and Odessa shredder are included in the functional relationships for specific energy versus product size, the correlation coefficients drop to approximately 0.7 as shown in Table 14.

The suspected reason for the different behavior of the Newell hammermill as compared to the other hammermills is addressed in the section, "Comparison of Cockeysville and Odessa Results".

TABLE 14. SPECIFIC ENERGY REQUIREMENTS VERSUS PRODUCT SIZE UTILIZING TEST RESULTS FROM VERTICAL AND HORIZONTAL HAMMERMILLS

Equation	Correlation Coefficient
Air Dry Weight Basis	
$E_o = 21.77\, X_o^{-1.20}$	0.71
$E_o = 60.17\, X_{90}^{-1.14}$	0.72
Wet Weight Basis	
$E_{o_w} = 16.30\, X_o^{-1.15}$	0.69
$E_{o_w} = 42.92\, X_o^{-1.09}$	0.69

MOTOR SIZING

With regard to the estimation of the proper size motor for shredding refuse at a specified rate, it must be remembered that gross power requirements are composed of the net power required for size reduction plus the freewheeling power (otherwise known as the idle power or power required when not shredding refuse). Typically, the freewheeling power represents about 10 percent of the full load rating of the motor thus leaving the remaining 90 percent available for size reduction.

An estimation of the net power required to produce a specified particle size can be found by multiplying the specific energy (E_{o_w}) by the anticipated flow rate ($\dot{m}_w$). Dividing the product by 0.9 will then produce a rough estimate of the motor power which would be required.

This derivation assumes a service factor of 1.0. The actual motor size chosen should account for normal variations in throughput. The tests showed that service factors were anywhere in the range of 12 to 73 percent based upon average power usage (Table 12).

POWER-FLOW RATE-MOISTURE RELATIONSHIPS

Although the trend for increased power requirements as throughput increases is generally recognized, there is a paucity of data available in the literature to support this contention. In this section data are presented to quantify the trend indicated above. Plots of net power versus flow rate (on a wet weight basis) show the dependence of net power requirements on throughput (Figures 46 through 52).

A second commonly made observation regarding the shredding of municipal solid waste is that higher moisture contents often lead to reduced power requirements due to a combination of the effects of lubrication and a degradation in the strength of the fibrous components of refuse.

To show how flow rate and moisture affect power requirements for the systems tested, a multiple regression analysis was carried out for each set of data. The multiple regression analyses were based on the assumption that the curves which which would best describe the experimental results, shown graphically in Figures 46 through 52, could be represented by an equation of the form

$$P_n = A \dot{m}_w^{B}(1-MC)^{C} \tag{18}$$

where P_n = net power (kw);
$\dot{m}_w$ = flow rate of refuse through the shredder (T_wPH); and
MC = fractional moisture content of the refuse.

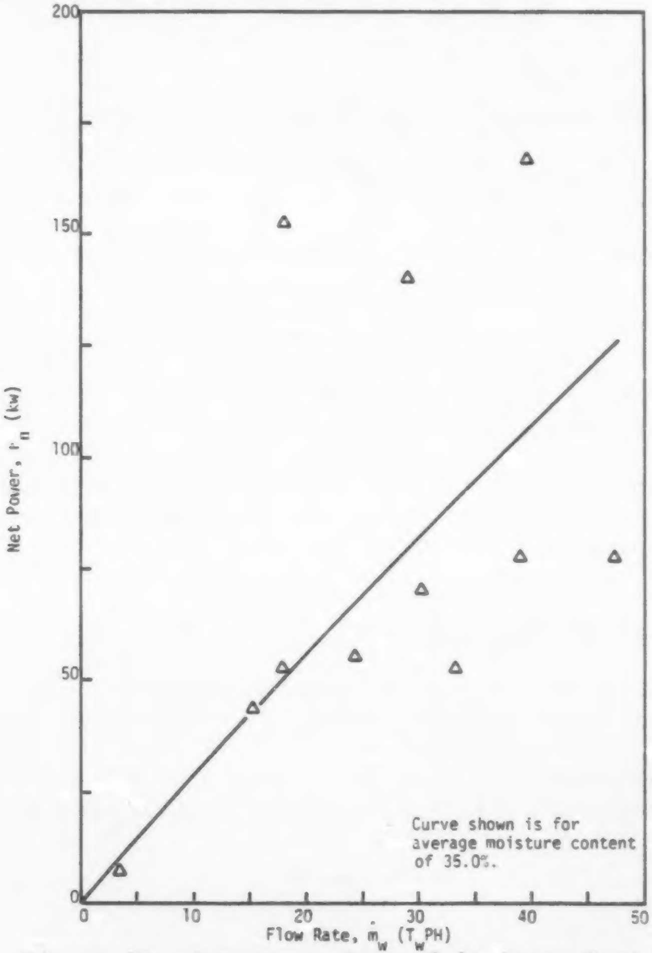


Figure 46. Net power draw of Appleton East Mill.

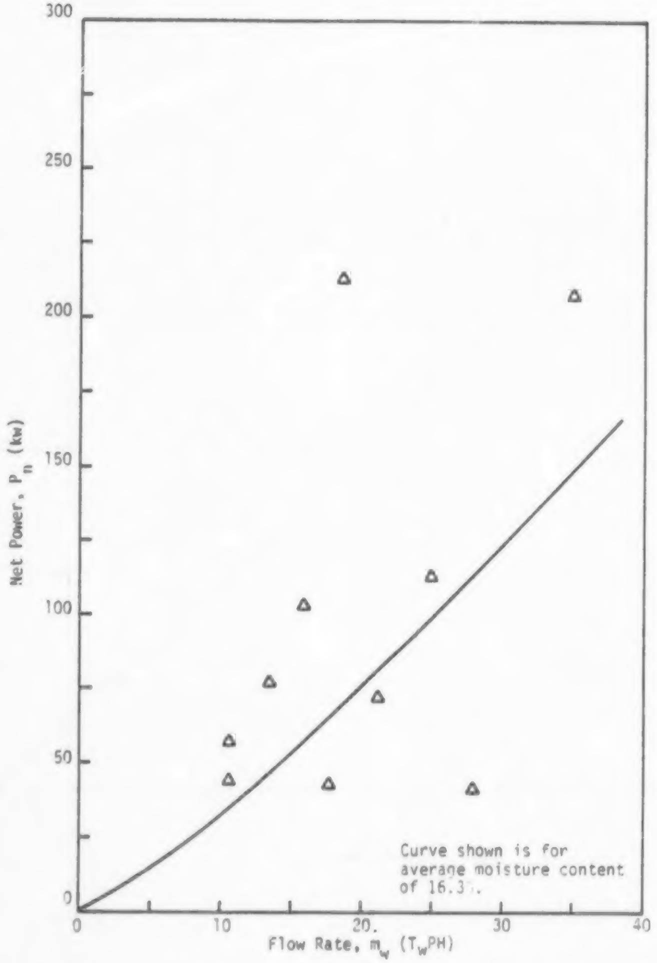


Figure 47. Net power draw of Ames primary shredder.

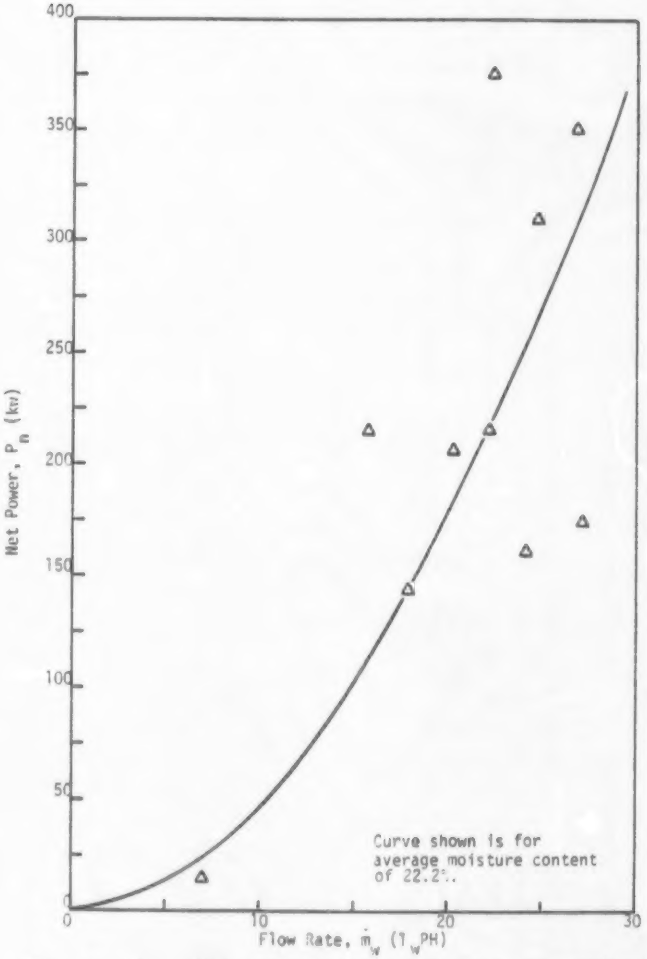


Figure 48. Net power draw of Ames secondary shredder.

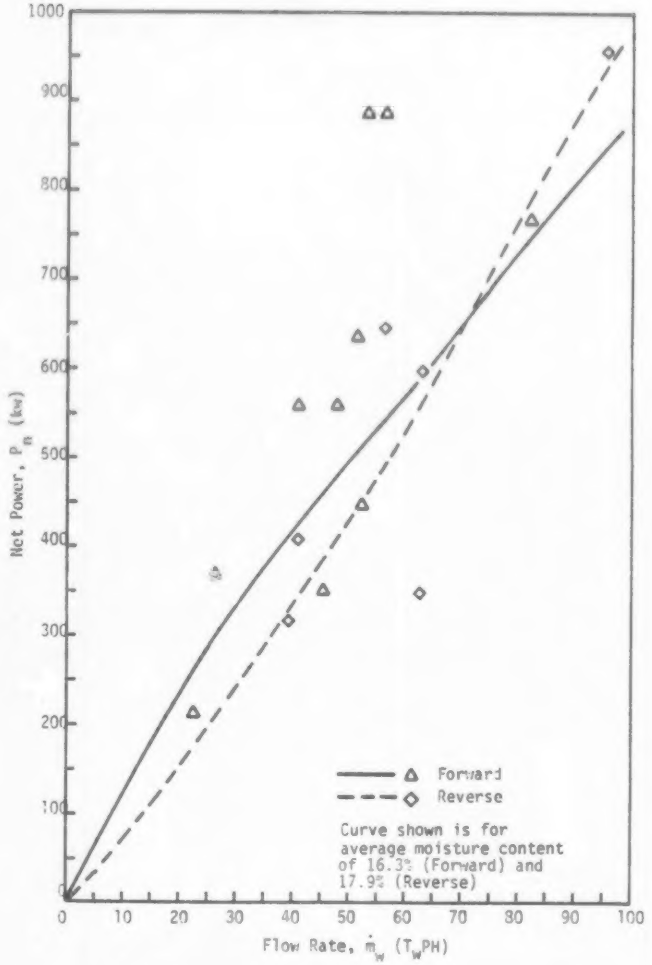


Figure 49. Net power draw of Cockeysville #1 shredder.

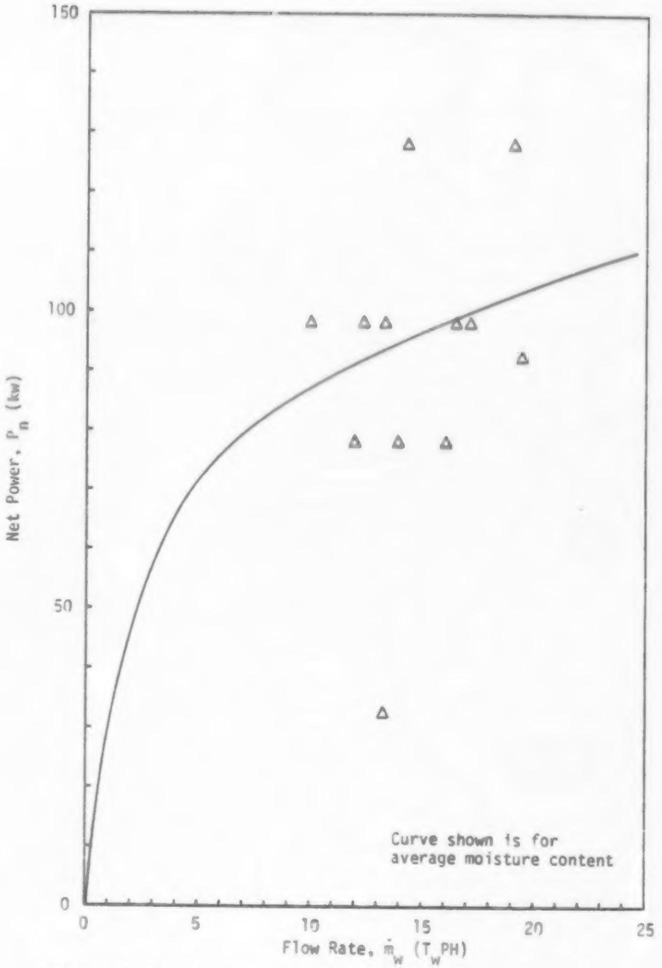


Figure 50. Net power draw of Great Falls 20TPH shredder.

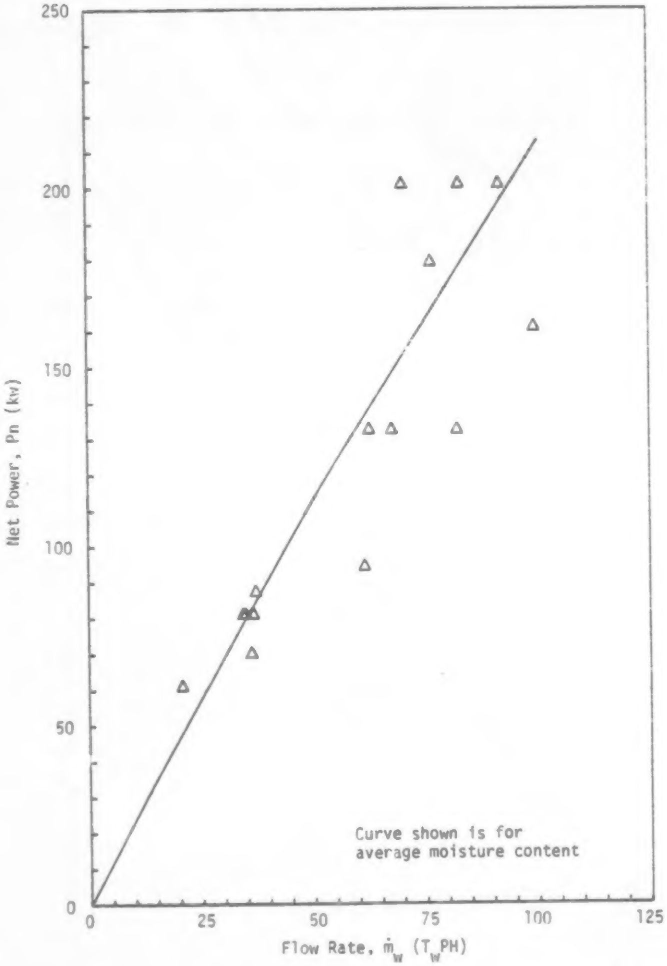


Figure 51. Net power draw of Tinton Falls shredder.

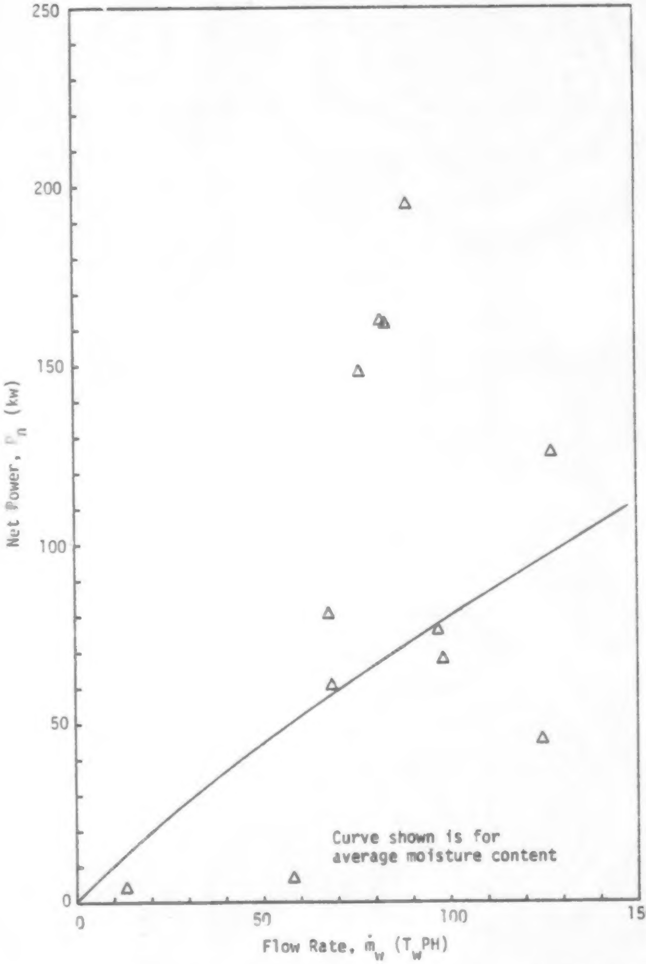


Figure 52. Net power draw of Odessa shredder.

The exponents B and C in equation 18 determine how power requirements change with flow rate and moisture content respectively, while the coefficient A affects the magnitude of the power requirements. Positive values for the exponents B and C indicate that power increases with flow rate but decreases as moisture content increases. The equations resulting from the regression analyses are presented in Table 15.

An examination of the information contained in Table 15 reveals that the assumed form of the curve fits the experimental data relatively well except in the case of Great Falls. The goodness-of-fit is indicated by the correlation coefficient, R. An exact match between the experimental data and the assumed form of the curve will yield a value for R of ± 1 while no correlation will yield a value of zero. The Cockeysville reverse data was fit best by the curve ($R = 0.96$) while the Great Falls data had the worst fit ($R = 0.28$).

The poor fit of the Great Falls data is speculated to be a consequence of the design and internal configuration of the shredders. To understand the rationale behind such speculation, one must understand the assumptions that are implicit in the development of equation 18, namely:

1. The net power is a function of the mass and moisture content of the material actually held within the mill;

2. The flow rate and mass of material within the shredder (the holdup) are related by a power curve or, in other words, the holdup equals some

TABLE 15. RESULTS OF MULTIPLE REGRESSION ANALYSIS

NET POWER AS A FUNCTION OF FLOW RATE AND MOISTURE CONTENT

Shredder	Correlation coefficient	Number of data points	Equation
Appleton east	0.85	11	$P_n = 6.33\ \dot{m}_w^{0.94}\ (1\text{-MC})^{1.54}$
Ames primary	0.74	10	$P_n = .62\ \dot{m}_w^{1.20}\ (1\text{-MC})^{-7.04}$
Ames secondary	0.93	10	$P_n = .28\ \dot{m}_w^{1.92}\ (1\text{-MC})^{-2.84}$
Cockeysville #1, forward	0.92	6	$P_n = 47.04\ \dot{m}_w^{0.82}\ (1\text{-MC})^{4.79}$
Cockeysville #1, reverse	0.96	6	$P_n = 6.40\ \dot{m}_w^{1.18}\ (1\text{-MC})^{2.01}$
Cockeysville #1, combined	0.91	12	$P_n = 21.85\ \dot{m}_w^{0.90}\ (1\text{-MC})^{2.25}$
Great Falls 20 TPH	0.28	12	$P_n = 39.97\ \dot{m}_w^{0.27}\ (1\text{-MC})^{-0.63}$
Tinton Falls	0.85	12	$P_n = 4.05\ \dot{m}_w^{0.94}\ (1\text{-MC})^{1.66}$
Odessa, forward	0.91	12	$P_n = 0.14\ \dot{m}_w^{0.84}\ (1\text{-MC})^{-12.64}$

constant factor multiplied by the flow rate which has been raised to some power; and

3. The load is distributed uniformly along the axis of the shredder.

It is evident that in the case of a vertical hammermill such as the one used in Great Falls, the load is not uniformly distributed along the shredder axis. The hammers in the upper portion of the mill (the breakers) and the hammers at the bottom (the sweeps) contribute relatively little to the size reduction of material within the mill. This observation is corroborated by the low rates of hammer wear exhibited in these areas when compared to the wear of the hammers in the throat section (cutters). Most of the size reduction is done in the latter section where the clearance between the hammers and the mill liners is least. Although the power requirements of the narrow clearance area may indeed be fit by equation 18, it is not possible to obtain moisture and flow rate data for material within this section of the mill without knowing substantially more about how material is transported through the mill.

Values of the exponent B range from 0.27 (Great Falls) to 1.92 (Ames secondary). The very low value for Great Falls stems from the problem mentioned above. The relatively high value obtained for the Ames secondary shredder is believed to be derived from the fact that, at the time of the tests, the hammers had been worn to less than half the original length and were not shredding refuse very effectively. In most cases, however, the value of B is close to unity thus indicating that power requirements are almost directly proportional to the flow rate.

The exponent C ranges from -12.64 (Odessa) to 4.79 (Cockeysville, forward). Positive values for C indicate that the net power required decreases as moisture increases, while negative values indicate that power increases with moisture content. Contrary to expectations, some negative values of C can be noted. Since such a result runs counter to most previous experience, it is difficult at the present time to offer a reasonable explanation of the phenomenon without performing a more extensive series of tests.

The curves drawn in Figures 46 through 52 represent the power equations listed in Table 15 with the value of the moisture content (MC) in the equations replaced by the average value calculated for the respective sites.

DISCUSSION OF APPLETON HOLDUP DATA

The Appleton site was the only one at which holdup data could be gathered. Holdup, as mentioned earlier, is the mass of material actually held within the shredder at any given moment. It has been demonstrated that the power requirement of a shredder will remain relatively constant regardless of flow rate and grate spacing as long as the shredder holdup also remains constant (1). In other words, if the grate spacing of a shredder is changed and the flow rate is adjusted so as to provide the same holdup as a different flow rate did before the grate spacing modification, then the power requirements of the shredder will be unchanged. The implication is that, although power is a function of holdup, the shredder holdup is a function of flow rate and the design of the shredder.

A regression analysis of the power-holdup and holdup-flow rate data (Appendix A) shows that the power-holdup data may be described by an equation of the form

$$P_n = 1.60284H^{0.95716} \tag{19}$$

and the hold-up flow rate data may be described by

$$\dot{m}_w = 0.50749H^{1.04402} \tag{20}$$

where: P_n = net power (kw);
H = shredder holdup (kg);
$\dot{m}_W$ = flow rate (T_WPH).

The regression coefficients are 0.82 and 0.90 for equations 19 and 20 respectively.

Flow rate is shown as a function of holdup in equation 20 because the flow rate data gathered were output flow rates while, strictly speaking, holdup is a function of both input and output flow rates. Moisture is neglected as a parameter in equation 19 since the moisture contents were determined from the flow rate samples and hence may not have been representative of the holdup as well.

DISCUSSION OF THE RESULTS FOR THE AMES PRIMARY AND SECONDARY SHREDDERS

Although both the Ames primary and secondary shredders are American Pulverizer model 6090 shredders and are driven by identical motors, the internal configuration of the hammers and grates differ greatly as evidenced by the different equations developed for each shredder. Principal among the internal shredder variations are size and spacing of grate bars and hammer design. It has been demonstrated at the University of California Solid Waste Processing Laboratory in Richmond, Ca. (1,3) that:

1. The power requirement of a shredder is dependent on the mass of material held within the shredder (the shredder holdup);

2. For a constant grate spacing the shredder holdup increases with flow rate;

3. For a constant flow rate the shredder holdup increases as the grate openings are decreased in size; and

4. Power requirements decrease with hammer rotational velocity.

It is thus expected that the power requirements of the secondary shredder with its substantially smaller grate openings would be significantly higher than that of the primary shredder. Examination of the power-flow rate plots for the two shredders while inserting trial flow rate and moisture data into the equations developed for the Ames shredders show that the secondary shredder does indeed require more power than the primary shredder. It has already been noted that reducing the rotational velocity of the shredder (causing lower hammer tip velocities) results in decreased power requirements (3). Since shortening the hammer length for a fixed rotational velocity also reduces the hammer tip velocity, decreased power requirements may be expected for shorter hammers also. At Ames the hammers are allowed to wear out before replacing them (rather than regularly retipping them), and it is reasonable to expect the ratio of primary to secondary power requirements to vary as the difference in primary and secondary hammer lengths changes due to wear. At the time of the tests the hammers on the secondary shredder were already substantially worn as shown in Figure 13. Consequently the only data collected is for a "worn down" condition of the secondary hammers. From the standpoint of optimization of two-stage size reduction, it would be interesting to obtain power, flow rate, moisture content and size distribution data for the condition of new hammers in the secondary mill and then compare the energy requirements of primary and secondary shredders.

At this point it is not possible to predict what the power ratio would have been had the primary and secondary hammers been the same length. Due to the lack of data for other hammer lengths on either shredder, it is impossible to quantitatively predict the power requirements as the hammers wear (other than predicting the power should decrease) even though the plant personnel claim that the power requirements are in fact less for the well worn hammers than for new hammers.

Although low power requirements are desirable from a processing standpoint, a potential pitfall of a design based on short hammers is limitation of throughput capacity of the shredder, i.e. as the hammers get shorter the maximum flow rate through the shredder can be expected to decrease.

DISCUSSION OF BI-DIRECTIONAL ROTATION OF COCKEYSVILLE #1 SHREDDER

The Cockeysville shredders are reversible Tracor-Marksman model A60 hammermills. Since the interior of the shredder is axially symmetric, the power requirements ideally should be identical for either forward or reverse operation although the plant operating personnel claim that operating in the forward direction requires more power. From the plot of the Cockeysville power-flow rate data in Figure 49, it is not readily apparent which direction actually requires more power to process the same flow rate. The equations resulting from the regression analysis, however, show that forward operation does indeed require more power to process the same flow rate.

The probable cause of this difference was identified by the plant manager, Ken Cramer, as grate blockage during forward operation caused by shredded refuse adhering to the inclined back of the discharge hopper. A cross-sectional view of the shredder is presented in Figure 53. While operating in forward rotation, shredded refuse adheres to the inclined back of the discharge hopper, particularly in the corners. Eventually enough material becomes packed into the region labeled A to block the openings between the grates which effectively reduces the area through which shredded refuse may be discharged. As a result more material resides in the shredder for the

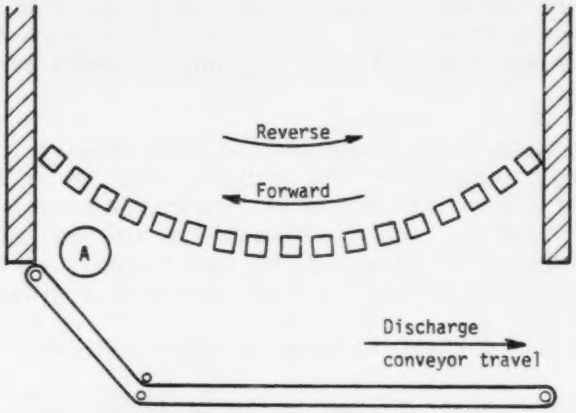


Figure 53. Cross-sectional view of discharge under #1 shredder at Cockeysville

same flow rate (the holdup is increased) and the power required to process refuse at the same rate is increased as well.

DISCUSSION OF GREAT FALLS VERTICAL HAMMERMILL RESULTS

The vertical hammermill in Great Falls exhibited substantially different behavior than the rest of the shredders which were tested. As mentioned earlier, the difference is believed to stem from the fact that the shredding of refuse is highly non-linear along the length of the mill, while the model assumes uniform or at least linear shredding along the mill.

To gain a better understanding of the operation of the vertical hammermill, the specific energy on a wet basis, E_{o_w}, was plotted against wet flow rate, $\dot{m}_w$, as in Figure 54. Three of the points may be identified as outlyers, and if these points are neglected and a regression analysis done on the remaining data, a curve drawn through the remaining points is best described by the equation

$$E_{o_w} = 89.26\ \dot{m}_w^{-0.99} \tag{22}$$

The correlation coefficient for equation 22 is -0.88 which indicates that 78 percent of the variation in specific energy is explained by the variation in flow rate. Equation 22 implies that the specific energy is inversely proportional to the flow rate. Recalling that the definition of specific energy is net power divided by the flow rate, multiplying the left side of equation 22 by the flow rate would then predict the net power. Multiplying the right hand side of equation 22 by the flow rate yields

$$P_n = 89.26\ \dot{m}_w^{0.01} \tag{23}$$

In other words, the net power is seen to be nearly constant and only slightly affected by the flow rate. Such a result is born out by the plot of net power versus flow rate in Figure 50, where points are congregated about 90 kw.

The relatively constant net power over a wide range of flow rates at Great Falls is directly opposed to the results obtained at the rest of the sites indicating that a vertical hammermill operates on substantially different principles than horizontal hammermills and vertical ring grinders, and that it may be impossible to apply the usual model, as described by equation 18, to any portion of the vertical hammermill grinding zone.

DISCUSSION OF TINTON FALLS VERTICAL RING SHREDDER RESULTS

The vertical ring shredder tested in Tinton Falls exhibited behavior very similar to that of horizontal hammermills indicating that the size reduction process may be relatively linear along the axis of the mill. One notable aspect of the ring grinder's operation was the relative freedom from large spikes in the power requirements. A typical recording of the power requirements of a horizontal hammermill shows large power fluctuations as

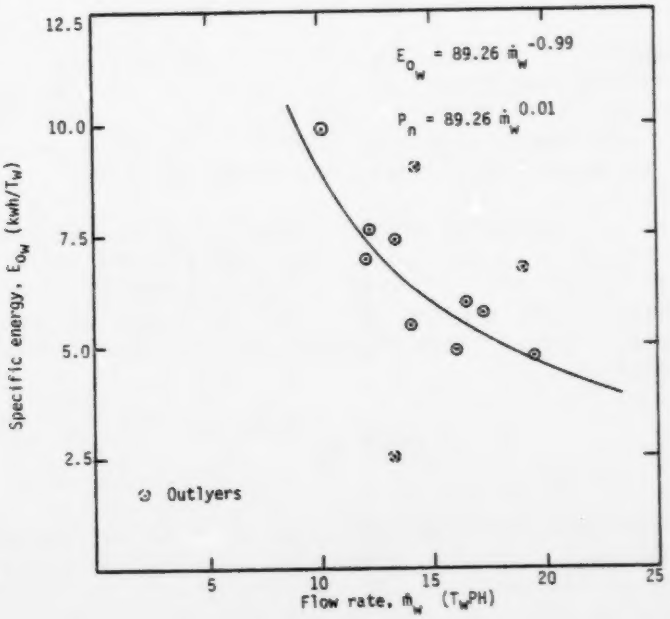


Figure 54. Relationship between flow rate and specific energy for Great Falls vertical hammermill.

material is fed to the mill while the recording of the power for the ring shredder shows a more uniform power level. Figure 55 shows a comparison between representative power recordings for the ring shredder (top graph) and a horizontal hammermill (bottom graph). The vertical scale is the same in both graphs as is the horizontal scale. The more uniform power level indicated by the recording for the ring shredder indicates that shock loading of the mechanical components of the ring shredder will be less than corresponding shock loads in hammermills.

As indicated by the relatively low value of the leading coefficient in the power equation for Tinton Falls (shown in Table 15), the power requirements for the Tinton Falls shredder are relatively low when compared to the other shredders (omitting the Odessa shredder). Part of the reason for the low power requirements is explained by the fact that the grinders inside the shredder were well worn at the time of the tests. The plant manager, John Gray, indicated that power requirements do temporarily increase when new grinders are installed and that as the grinders wear, the power requirements gradually decrease.

COMPARISON OF COCKEYSVILLE AND ODESSA RESULTS

The specific energy required to produce an equivalent particle size was significantly lower for the Odessa shredder than for any other shredder tested. In view of the similarity in physical characteristics between the shredder in Odessa and those at the Cockeysville site, such a result is highly significant. The differences between the Odessa and Cockeysville shredders are:

1. Mill length: Odessa is 2.59 meters while Cockeysville is 2.74 meters;
2. Motor size: Odessa has a 373 kw motor while Cockeysville has 746 kw motors; however, the type of motor (wound rotor) is the same for both shredders;
3. Grate spacing: Odessa has 24.1 x 36.5 cm openings while Cockeysville has 20.3 x 35.6 cm openings;
4. Total grate opening: Odessa has 3.97 m^2 of grate openings while Cockeysville has 3.54 m^2 of grate openings; and
5. Number of hammers: Odessa has 14 while Cockeysville has 24.

Each of the above factors may contribute to the power requirements of a shredder, although the prime contributing factor is suspected to be the difference in number of hammers for the case of Cockeysville and Odessa.

In order to show how the power requirements of the Odessa and Cockeysville shredders differ, the characteristic product size was chosen as a basis for comparison. Both the Odessa and the Cockeysville data were examined for relations between characteristic size and flow rate. Although no statistically significant relation for the Cockeysville data was found, the

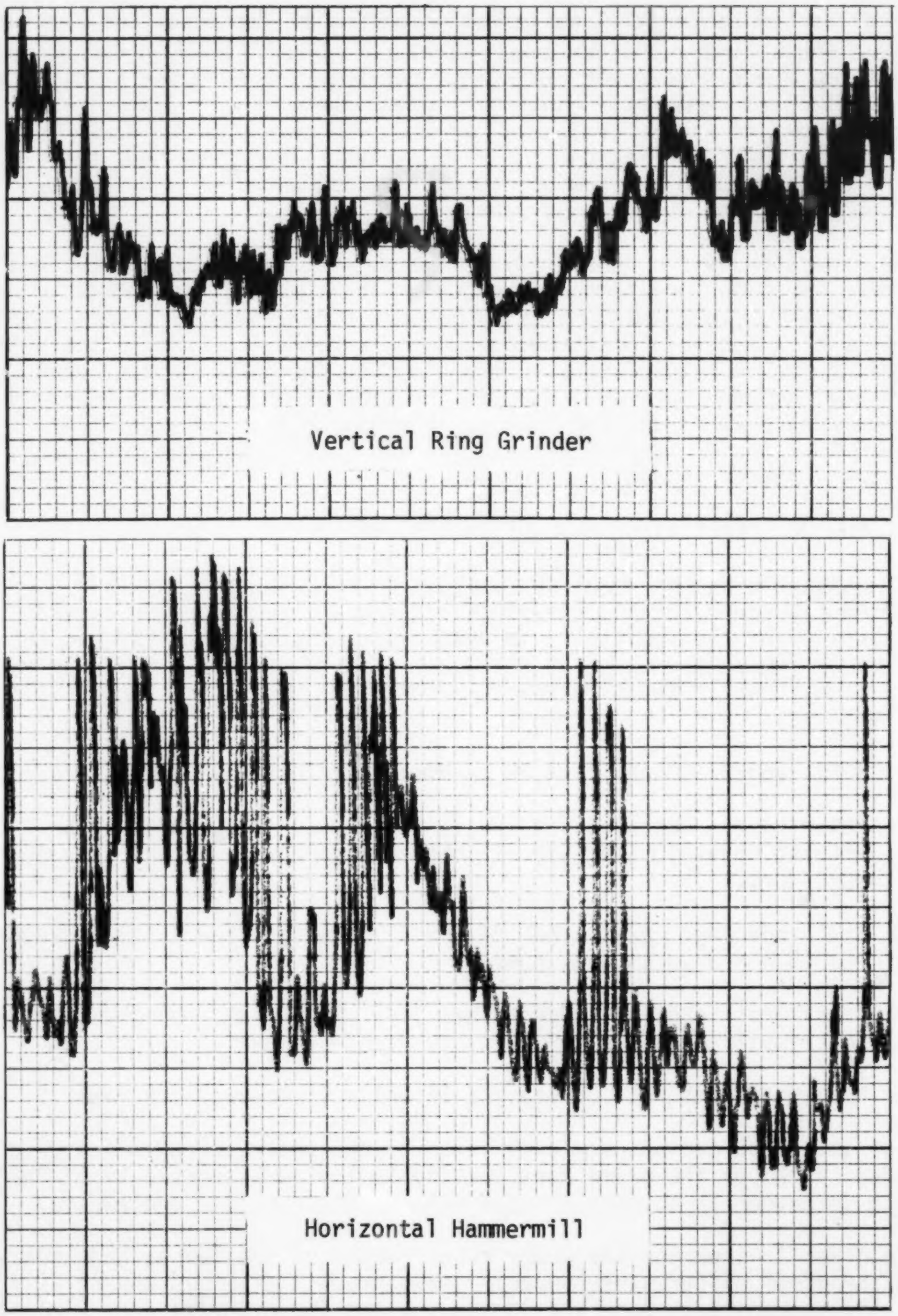


Figure 55. Representative hammermill and ring shredder power recordings.

Odessa data clearly showed an inverse relationship between characteristic size and flow rate.

The relation between the wet flow rate, $\dot{m}_w$, and characteristic size, X_o, obtained at Odessa is best described (correlation coefficient equal to -0.86) by the equation

$$X_o = -0.034 \dot{m}_w + 6.03 \tag{24}$$

Equation 24 and the data it describes are plotted in Figure 56.

To compare the Odessa results with the Cockeysville results, an auxiliary axis for the Cockeysville flow rates was drawn below the Odessa flow rate axis in Figure 56, and the Cockeysville data was plotted such that the average Cockeysville characteristic size fell on the line describing the Odessa data. The average characteristic size and flow rate found at Cockeysville were 2.1 cm and 49.5 T_WPH, respectively. Examination of the Odessa rate axis shows that a characteristic size of 2.1 cm would be expected from the Odessa shredder if the flow rate were 114.3 T_WPH.

Assuming a constant moisture content of 20 percent, the net power required to produce a characteristic size of 2.1 cm would be 124.9 kw and 441.7 kw for Odessa and Cockeysville, respectively. The specific energy required to produce a characteristic particle size of 2.1 cm is thus 1.1 kwh/T_W for Odessa and 8.9 kwh/T for Cockeysville. If it is assumed that the Odessa refuse is not substantially different than that at Cockeysville, then most of the variation may be attributed to one or all of the aforementioned physical differences between the shredders.

There has been some speculation (1) on the effect of various physical characteristics of a horizontal hammermill on the operating parameters, but, as yet, there exists no definitive answer to such speculation. From a design standpoint, the effect of the physical characteristics of a hammermill on its operation is one of the least understood areas and most in need of further research.

Due to the fact that significant energy savings are possible, further research is needed in order to discern the reason for the low energy consumption exhibited by the Odssa shredder. Such research could include varying the number of hammers, the grate spacing, and the hammer geometry while measuring energy consumption and flow rate.

SPECIFIC ENERGY COMPARISON OF SINGLE VERSUS MULTIPLE STAGE SIZE REDUCTION OF MSW

Some of the data collected at the Ames and Cockeysville sites can be used to compare single and multiple stage size reduction of solid waste. This comparison is, of course, site specific and due to the nature of the study, only a limited amount of data is available for comparison. In order to reach any general conclusions regarding the efficacy of single stage versus multiple stage size reduction, a rigidly constructed test program is

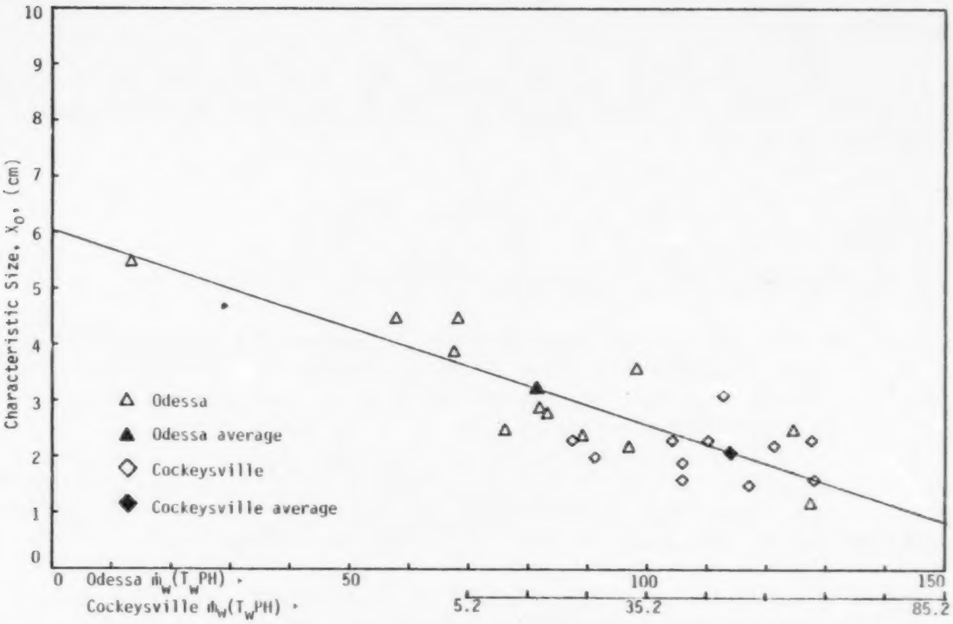


Figure 56. Comparison between Odessa and Cockeysville flow rate-size relationships.

needed. The nature of such a program (for instance, requiring changes of grate openings in each shredder tested) would probably preclude testing at commercial plants due to interruptions in normal plant operation and operating procedure.

Bearing the preceding comments in mind, an analysis of the Ames and Cockeysville data allows a comparison of a specific case of single versus multiple stage size reduction. The comparison involves examination of gross and net power consumption (P_G and P_N, respectively), mass flow rates of refuse ($\dot{m}_w$), and product size (X_0). For the purposes of comparison of processing alternatives, the criterion of equivalent product size from both single shredding at Cockeysville and secondary shredding at Ames was used. The data allow the comparison of three such cases for which an average characteristic product size (X_0) of 1.6 cm was calculated, as shown in Table 16.

In order to compare the power requirements of single versus multiple stage size reduction, the moisture content (MC) must be specified as well as the product size (already chosen as 1.6 cm). For purposes of comparison, the average moisture content was taken as 20.5 percent for a hypothetical refuse encountered at Ames and Cockeysville. As previously discussed, net power requirements for size reduction can be expressed as

$$P_N = A\dot{m}_w{}^B(1-MC)^C \qquad (25)$$

where A, B, and C are constants determined by curve fitting techniques.

Since we have specified MC as 20.5 percent, equation 25 reduces to

$$P_N = A\dot{m}_w^{\,B}(0.795)^C \tag{26}$$

The constants A, B, and C have been calculated for equation 26 for the Ames primary and secondary shredders and for the Cockeysville shredder.

For the Ames primary and secondary shredders, the most appropriate equations for net power are

$$P_N = 0.619\ \dot{m}_w^{\,1.197}(0.795)^{-7.039} \tag{27}$$

and

$$P_N = 0.278\ \dot{m}_w^{\,1.922}(0.795)^{-2.843} \tag{28}$$

respectively, where $\dot{m}_w = 21.6$ T_wPH since that throughput produces the required average produce size (X_0) of 1.6 cm. For shredder #1 at Cockeysville, the equation for net power (calculated by combining data for both forward and reverse directions of rotation) is

$$P_N = 21.85\ \dot{m}_w^{\,0.899}(0.795)^{2.247} \tag{29}$$

wherein $\dot{m}_w = 52.2$ T_wPH since that throughput produces the desired average product size (X_0) of 1.6 cm.

TABLE 16. SHREDDING DATA USED TO DEVELOP COMPARISONS BETWEEN SINGLE AND MULTIPLE STAGE SIZE REDUCTION

Shredder		$\dot{m}_w$ (TPH)	X_o (cm)	Test[a] No.
Cockeysville		52.3	1.5	6-F
		63.2	1.6	7-R
		41.1	1.6	8-R
	Average	52.2	1.6	
Ames Secondary		15.8	1.5	7
		22.2	1.6	6
		26.9	1.6	2
	Average	21.6	1.6	

[a] Test numbers refer to tests in data summaries in Appendix A.

The solution of equations 27, 28, and 29 allows calculation of the total net power required to produce the required product size. The total net power required at Ames and Cockeysville are 319.0 and 456.8 kw, respectively. The specific energy (on a wet weight basis, $P_N/\dot{m}_W$) for Ames and Cockeysville are 14.8 and 8.8 kwh/T_W, respectively. Consequently, the specific energy required to produce the required product size at Ames is 168 percent of the energy requirement at Cockeysville. Table 17 contains a summary of the net power and specific energy reqired to produce a specified size of 1.6 cm at the Ames and Cockeysville sites.

TABLE 17. NET POWER AND ENERGY REQUIREMENTS FOR SINGLE AND MULTIPLE STAGE SIZE REDUCTION

Shredder	MC (%)	$\dot{m}_W$ (T_WPH)	P_n (kW)	E_{O_W} (kwh/T_W)
Ames Primary	20.5	21.6	123.1	5.7
Ames Secondary	20.5	21.6	195.9	9.1
		Totals	319.0	14.8
Cockeysville	20.5	52.2	456.8	8.8

Calculation and scrutiny of the gross energy requirements(i.e. net specific energy plus freewheeling energy) for both sites allows establishment of the overall energy requirement to produce an equivalent product size from each site. As an example, size reduction of 100 tons of refuse is considered and the appropriate calculations are carried out, as shown in Table 18. When the freewheeling energy contribution (column G) is added to the

TABLE 18. CALCULATION OF REQUIRED GROSS SPECIFIC ENERGY TO OBTAIN EQUIVALENT PRODUCT SIZE FOR AMES AND COCKEYSVILLE

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
			B ÷ A		B x D		C x F	G + E	H ÷ B
Site	Mass Flow Rate ($\dot{m}_W$)	Tonnage Shredded (T_W)	Time (Hr)	Net Specific Energy-E_{OW} (kwh/T_W)	Net Energy (kwh)	P_{FW} (kw)	Freewheeling Energy (kwh)	Gross Energy (kwh)	Gross Specific Energy (kwh/T_W)
Ames	21.6	100	4.6	14.8	1480	93.7[a]	431	1911	19.1
Cockeysville	52.2	100	1.9	8.8	880	66,1	126	1006	10.1

[a] Primary P_{FW} = 53.2; Secondary P_{FW} = 40.5

net energy for size reduction (column E), the result is the gross energy required to yield an average product size of 1.6 cm at each site. These gross energy requirements are 1911 and 1006 kw for size reduction of 100 tons at Ames and Cockeysville, respectively (column H). Division of these gross energy requirements by 100 tons yields the gross specific energy, namely 19.1 kwh/T_W for the former site and 10.1 kwh/T_W for the latter site (column I). On the basis of overall energy consumption, Ames would require almost twice as much energy as Cockeysville to produce an average product size of 1.6 cm.

Although this result is startling, one should not jump to any hasty conclusions with respect to the effectiveness of single versus multiple stage size reduction. In particular, it must be emphasized that the preceding comparison is only for a specific case. The effects of other variables upon single and multiple stage size reduction, for example, throughput, size of grate openings, etc., cannot be ascertained from these data. Neither can it be judged whether or not the two shredder stages at Ames are optimized with respect to energy consumption. It is a fact that at Ames the secondary shredder uses considerably more energy per unit mass of refuse than the primary shredder. This fact alone points to the possibility of optimizing the shredder operation at Ames. Proper optimization of the shredder combination at Ames could potentially reduce the present energy requirement as developed in this example such that the overall energy consumption would approach that estimated for the single shred at Cockeysville.

RESULTS OF THE HAMMER WEAR STUDIES

Since each processing facility had its own particular type of solid waste and set of operating conditions, the results of the hammer wear tests are reported here by individual test site. Later, generalizations concerning hammer wear will be presented and discussed.

Appleton (Refer to Table 19)

Test results of hammer wear in the east mill (where the T-1, type B hammers were hardfaced with Stoody 2134) show an average weight loss per hammer per ton (denoted as w_i) of refuse processed equal to 9.44×10^{-4} kg. Wear of a full complement of hammers (W_o), i.e. 24 hammers, is 0.023 kg/T_W.

Test results of hammer wear in the west mill elucidate the wearability of McKay 48, McKay 50 TiC, Stoody 2134, and Amsco Super 20. These alloys exhibit values of w_i of 4.84×10^{-4}, 3.30×10^{-4}, 3.30×10^{-4}, 3.60×10^{-4}, and 2.73×10^{-4} kg/Hammer-T_W, respectively. When these values are corrected to a full hammer complement of 48 hammers, the W_o values are 0.023, 0.016, 0.017, and 0.013 kg/T_W for McKay 48, McKay 40 TiC, Stoody 2134, and Amsco Super 20, respectively.

Two important results can be gleaned from the data. First, as-deposited hardness appears to correlate inversely with W_o. From Table 19 and Figure 57, W_o can be seen to be least for the hardest hardfacing alloy and greatest for the softest alloy. The second important result stems from comparison of W_o values for Stoody 2134 obtained in the east and west mills. The

TABLE 19. APPLETON HAMMER WEAR EXPERIMENTS

Alloy	Hardness[1] (Rc)	Number of Hammers Weighed	Test Tonnage (T_w)	Total Weight Loss (Kg)	Avg Wt Loss (w_i) (Kg/Hammer-T_w)	Wear of Full Hammer Complement (W_0) (Kg/T_w)
EAST MILL						
Stoody 2134	48	12	398.32	4.51	9.44×10^{-4}	0.023
WEST MILL						
McKay 48	38	12	141.30	0.82	4.84×10^{-4}	0.023
McKay 40 TIC	45	12	141.30	0.56	3.30×10^{-4}	0.016
Stoody 2134	48	12	141.30	0.61	3.60×10^{-4}	0.017
Amsco Super 20	56	7[2]	141.30	0.27	2.73×10^{-4}	0.013

[a] As-deposited hardness per manufacturer's literature

[b] Five hammers failed due to brittle fracture of hammer at midsection, reason for failure undetermined

two values are significantly different which possibly points out the unknown effects of refuse composition and operational variables, such as hammer geometry, base material of hammer, rpm, etc. Each of the above was different for the mills at Appleton (refer to Table 2). Because of the aforementioned

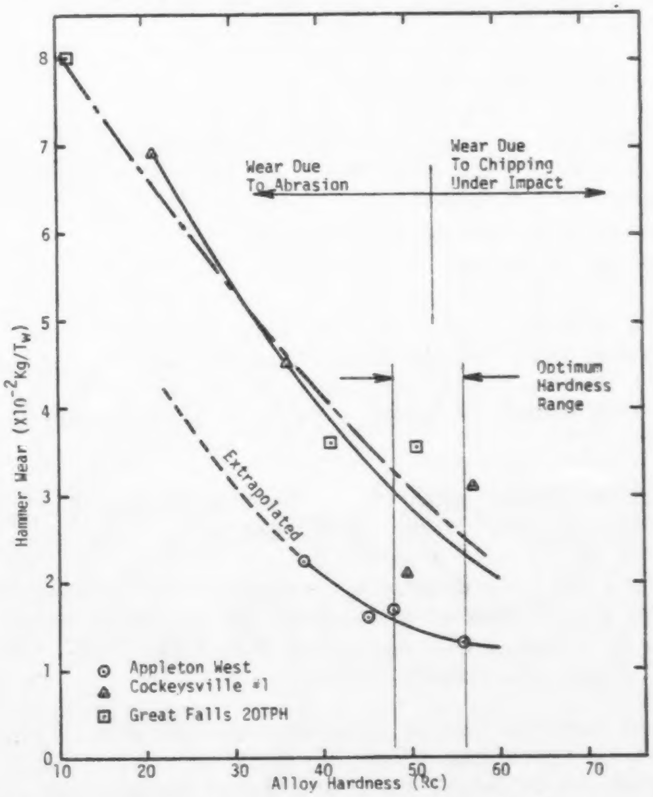


Figure 57. Hammer wear as a function of alloy hardness.

variations in refuse composition and operating parameters, comparisons of wear characteristics of different alloys are best accomplished by simultaneous testing, that is, employing the same, or similar methods, used in securing the Appleton west mill data.

Ames (Refer to Table 20)

After four months of shredding, the manganese hammers in the primary shredder exhibited an average weight loss per hammer per ton (w_i)of 5.50×10^{-4} kg. Corrected to a full complement of 48 hammers, this degree of wear (W_o) corresponds to 0.026 kg/T_w.

TABLE 20. AMES HAMMER WEAR EXPERIMENTS

Alloy	Hardness[a] (Rc)	Number of Hammers Weighed	Test Tonnage (T_w)	Total Weight Loss (Kg)	Avg Wt Loss (w_i) (Kg/Hammer-T_w)	Wear of Full Hammer Complement (W_o) (Kg/T_w)
Manganese Steel	14	48	14,253.83	376.59	5.50×10^{-4}	0.026

[a] Hardness per manufacturer's literature

Cockeysville (Refer to Table 21)

Average weight loss (w_i) of manganese steel hammers installed in shredder #2 was found to be 4.40×10^{-3} kg/Hammer-T_w. This value corresponds to a value of 0.106 kg/T_w for a full complement of 24 hammers. This value of W_o is significantly higher than the value of 0.026 kg/T_w that was obtained for manganese steel hammers used in the primary shredder at Ames. In addition, the average W_o value experienced at Cockeysville over a one and a half month period in early 1978 was 0.020 kg/T_w. The high rate of wear measured at Cockeysville (over 500 percent of normal) is attributed to the use of new hammers in the experiments and as a consequence of accelerated wear of the sharp corners during initial run-in.

Experimental results for wear of different hardfacing alloys applied to hammers installed in shredder #1 show values of w_i for Mangjet, Abrasoweld, McKay 55, and Faceweld 12 to be 2.88×10^{-3}, 1.87×10^{-3}, 0.89×10^{-3}, and 1.57×10^{-3} kg/hammer-T_w, respectively. When corrected to a full complement of 24 hammers, the degrees of wear (W_o) are 0.069, 0.045, 0.021, and 0.038 kg/T_w for Mangjet, Abrasoweld, McKay 55, and Faceweld 12, respectively.

TABLE 21. COCKEYSVILLE HAMMER WEAR EXPERIMENTS

Alloy	Hardness[a] (Rc)	Number of Hammers Weighed	Test Tonnage (T_W)	Total Weight Loss (Kg)	Avg Wt Loss (w_i) (Kg/Hammer-T_W)	Wear of Full Hammer Complement (W_0) (Kg/T_W)
SHREDDER #2						
Manganese Steel	14	12	305.36	16.11	4.40×10^{-3}	0.106
SHREDDER #1						
Mangjet	21	6	255.09	4.41	2.88×10^{-3}	0.069
Abrasoweld	36	6	255.09	2.86	1.87×10^{-3}	0.045
McKay 55	49	6	255.09	1.36	0.89×10^{-3}	0.021
Faceweld 12	57	6	255.09	2.41	1.57×10^{-3}	0.038

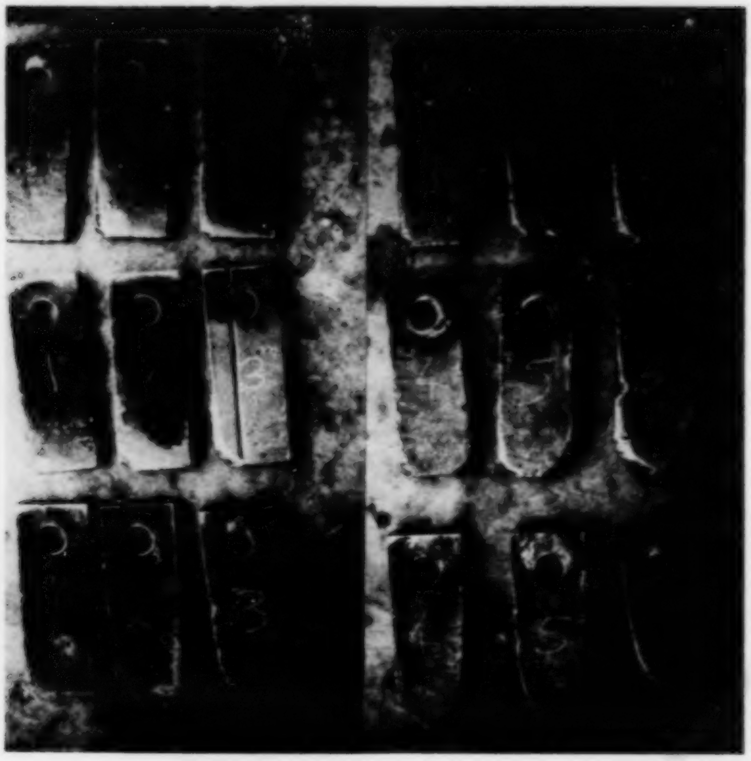
[a] As-deposited hardness per measurements at site

As in the case of the Appleton data, a general trend of descending wear exists for an ascension of as-deposited hardness values of the test alloys (shredder #1, Table 21 and Figure 57). The lone exception occurs for Faceweld 12 (the hardest alloy tested at 57 R_C) which exhibits greater wear (0.038 kg/T_W) than the next hardest alloy, McKay 55 (49 R_C), 0.021 kg/T_W). Reference is made to the fact that visual observation of the weld deposits after the test run showed that some of the Faceweld deposits had chipped away from the hammer base metal. The chipping phenomena could be due to poor weld deposition, incompatability with manganese steel and/or buildup alloy, and/or unsuitability of this alloy for refuse shredding. Although the reason for chipping was not resolved quantitatively, the suspicion is that the weld deposits of Faceweld 12 were too hard to absorb the shock loads that are associated with the size reduction of refuse. Hence, the welds of Faceweld 12 chipped under impact, whereas those of McKay 55 (which averaged eight points softer than Faceweld 12) were capable of withstanding the high impacts.

Great Falls (Refer to Table 22)

Results of the hammer wear experiments conducted in the Heil vertical shredder in Great Falls show the average weight loss per hammer (w_i) to be 0.080, 0.037, and 0.036 kg/T_W for bare 1060 hammers, hammers tipped with Stoody 2134, and hammers tipped with Amsco Super 20, respectively. Once again, the results show that the hardest materials wear the least, as graphically depicted in Figure 58.

The results in Table 22 are for the hammers in the bottom nine rows of the shredder. The hammers in the upper stage are changed infrequently and consequently were not used in the wear experiments. CRS estimates that the hammers in the lower nine rows undergo 90 to 95 percent of the total hammer wear.



Stoody 2134
Amsco Super 20
Bare

Figure 58. Hammers removed from Great Falls vertical hammermill. Note how wear visibly increases from left to right (hammer location within mill found in Figure 55).

The pattern of hammer wear showed that the hammers occupying the stages in the throat of the shredder (the cutting zone) and at the same level as the top of the discharge opening exhibited the greatest wear (see Figures 58 and 59), typically four to six times the wear of the sweep hammers (those hammers in the bottom stage which sweep material out of the shredder). Consequently, it may be concluded that most of the size reduction occurs in the cutting zone of the vertical shredder.

TABLE 22. GREAT FALLS HAMMER WEAR EXPERIMENTS

Alloy	Hardness[a] (Rc)	Number of Hammers Weighed	Test Tonnage (T_w)	Total Weight Loss (Kg)	Avg Wt Loss (w_i) (Kg/Hammer-T_w)	Wear of Full Hammer Complement (W_O) (Kg/T_w)
1060 Hammers	11[c]	8	178.3	4.40	3.08×10^{-3}	0.080[b]
Stoody 2134	41	9	178.3	2.26	1.41×10^{-3}	0.037[b]
Amsco Super 20	51	9	178.3	2.19	1.37×10^{-3}	0.036[b]

[a] As deposited hardness as measured

[b] Bottom three stages of shredder only (4 stages total); CRS estimates the hammers in the bottom three stages undergo 90 to 95% of the total hammer wear.

[c] Estimated, too soft to measure accurately

Odessa (Refer to Table 23)

Data supplied by the plant supervisor, Dwane Dobbs, were used to calculate the wear of hammers used in the Odessa mill. These bare hammers shredded 5,201 tons of refuse. The resultant average wear per hammer (w_i) was 2.13×10^{-3} kg/T_w. For a full complement of 14 hammers, the hammer wear was 0.030 kg/T_w, as shown in Table 23.

TABLE 23. ODESSA HAMMER WEAR EXPERIMENTS

Alloy	Hardness[a] (Rc)	Number of Hammers Weighed	Test Tonnage (T_w)	Total Weight Loss (Kg)	Avg Wt Loss (w_i) (Kg/Hammer-T_w)	Wear of Full Hammer Complement (W_O) (Kg/T_w)
Modified Hatfields Mn Steel Hammers	33	14	5,201	156.7	2.15×10^{-3}	0.030

[a] As deposited hardness as measured

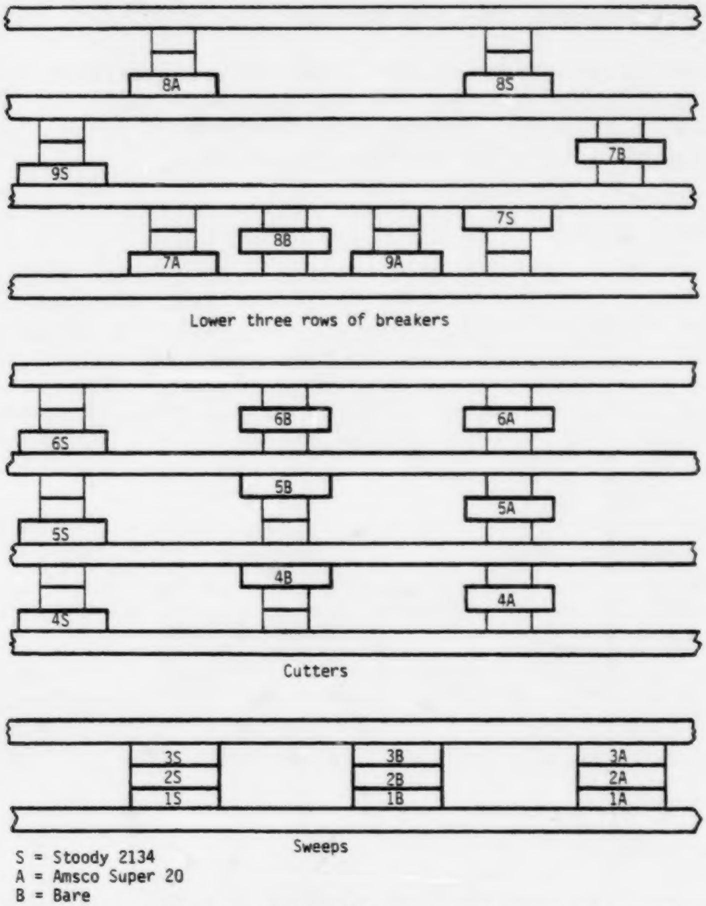

8A
8S
9S
7B
7S
8B
7A
9A
Lower three rows of breakers
6B
6A
6S
5B
5A
5S
4B
4A
4S
Cutters
3S
2S
1S
3B
2B
1B
3A
2A
1A
Sweeps
S = Stoody 2134
A = Amsco Super 20
B = Bare

Figure 59. Hammer installation pattern for Great Falls wear experiments.

Tinton Falls

Data supplied by the plant manager, John Gray, were used to determine the wear of the ring grinders used within the Carborundum vertical ring shredder. The ring grinders, which were not hardfaced, shredded 16,353 tons of refuse. The resultant average wear per hammer (w_i) was 2.13×10^{-3} kg/T_W. Wear for a full complement of sixty ring grinders was 0.027 kg/T_W, as shown in Table 24.

TABLE 24. TINTON FALLS WEAR EXPERIMENTS

Alloy	Hardness[a] (R_C)	Number of Grinders Weighed	Test Tonnage (T_w)	Total Weight Loss Kg	Avg Wt Loss (wi) (Kg/Hammer-T_w)	Wear of Full Hammer Complement (Wo) (Kg/T_w)
Nickel-Manganese	43	60	16,353	445.4	4.5×10^{-4}	0.027

[a] As measured on new ring grinders

COMPARISON OF HAMMER WEAR DATA AMONG SITES

Some general observations can be drawn from comparisons of the wear data among the sites. These observations are described below and are divided into the following headings: optimum alloy hardness range, mechanisms of hammer wear, and normalization of hammer wear data.

Optimum Alloy Hardness Range

The greatest rates of wear were sustained by hammers that exhibited low values of hardness. For the hardfacing alloys that were tested, as the hardness of the alloys increased, the degree of wear correspondingly decreased. The limiting factor at the high range of alloy hardness appears to be chipping of the welds under high impact loads. The trend of decreased hammer wear for harder alloys is apparent if one examines the data from the Appleton west mill, the Cockeysville #1 shredder, and the Great Falls 20 TPH shredder, as shown in Figure 57.

The optimum range of alloy hardness appears to lie within the range $48 \leq R_c \leq 56$ (shown in Figure 57) with the upper value limited by the chipping tendency of the welds under impact loading. The exact hardfacing alloy for a given shredding operation would have to be determined experimentally by testing a group of different hardfacings having as-deposited hardness values within the optimum range. For reasons that were mentioned before, testing a number of alloys under identical operating conditions (e.g. one alloy per hammer row) is the only valid method for comparing wear of alloys, and consequently this method is recommended for comparison purposes.

Mechanisms of Hammer Wear

Visual observation of worn hammers after testing showed abrasive wear to be the dominant mode of wear for alloys with R_c less than about 50 (Figure 57). For these alloys, impact loading appeared to damage at most 10 to 20 percent of the hammer surface. Whether these impact loads actually removed a significant degree of hammer material or only plastically deformed the hammer is unknown (particularly since abrasive wear would tend to smooth out any sharp edges resulting from impact chipping).

Impact chipping on the other hand was the dominant mode of wear for the hardest alloys tested (R_c greater than about 50) as shown in Figure 57. Consequently, the brittleness of the deposited alloy and its union with the base hammer material are the determining factors with regard to maximum wear of extremely hard alloys. The impacts apparent on the hammers coated with the softer alloys consequently represent the blows that cause the harder alloys to fail by means of brittle fracture.

Normalization of Hammer Wear Data

Comparisons of hammer wear data among sites must take into account the fineness of shred since operating experience has shown that wear increases as product size of shredded refuse decreases. In addition to size of the product, size of the feed material also may have a bearing on the degree of hammer wear. It has already been pointed out that the composition of the refuse at Ames and Cockeysville was different than that processed at the other four plants. The fact that refuse that was processed at Appleton, Great Falls, Tinton Falls, and Odessa tended to be more residential in nature than that processed at either Ames or Cockeysville implies that the characteristic size of the feed for those plants processing residential waste should be on the order of 12.7 cm. On the other hand, the commercial character of the waste encountered at Ames and Cockeysville implies that the feed size should be larger, on the order of 20.3 cm. These are average values for raw residential and commercial waste which are based upon previous experience and several waste composition and sizing studies conducted by CRS.

In order to account for variations of the size of the feed material and the shredded product size among different sites, a parameter termed the degree of size reduction, Z_0, is introduced. This term is defined as

$$Z_0 = (F_0 - X_0)/F_0 \tag{30}$$

where F_0 and X_0 are characteristic feed size and product size, respectively.

Values of the degree of size reduction range from a value of zero corresponding to no size reduction to a maximum limit of 1.0 corresponding to a product size of zero, or in other words, an infinite amount of size reduction. The latter limit is, of course, unachievable in actual practice.

Normalization of the wear data collected at Appleton's west mill, Great Falls' vertical shredder, and Cockeysville's shredder #1 using average Z_0 values and data from the three curves drawn in Figure 57 (summarized in Table 25) is demonstrated in Figure 60. The solid lines represent the data gathered during the wear experiments conducted at Appleton and Cockeysville. Although only two points are present for each curve, the general trend of increased wear at large values of Z_0 can be discerned nonetheless. Also apparent is the parametric effect of alloy hardness (R_c), i.e. for a particular value of Z_0 wear is greatest for the softest hardfacing alloy.

For comparative purposes, the wear data gathered at Great Falls has been normalized using the curve drawn for Great Falls in Figure 57. The normalized data, which is presented in Table 25, has been added to Figure 60 so that the hammer wear in a vertical shredder can be compared to that in horizontal shredders. For an equivalent degree of size reduction, the wear data for the hammers in the vertical mill tends to be slightly above the corresponding values for the horizontal hammermills. Since the data from only one vertical mill is available, the reason for the slight difference in wear depicted in Figure 60 cannot be ascertained at this point in time. The difference may be due to experimental error or an actual difference between the wearing mechanisms in vertical and horizontal hammermills.

TABLE 25. NORMALIZATION OF HAMMER WEAR MEASUREMENTS

Shredder	Alloy Hardness (R_c)	Average Characteristic Feed Size ($\overline{F}_o$) (cm)	Average Characteristic Product Size ($\overline{X}_o$) (cm)	Average Degree of Size Reduction ($\overline{Z}_o$)	Hammer Wear (W_o) (kg/T_w)
Appleton West Mill (Horizontal Hammermill)	28	12.7	5.6	0.56	0.034
	38	12.7	5.6	0.56	0.023
	48	12.7	5.6	0.56	0.016
	56	12.7	5.6	0.56	0.013
Cockeysville Shredder #1 (Horizontal Hammermill)	28	20.3	2.0	0.90	0.057
	38	20.3	2.0	0.90	0.043
	34	20.3	2.0	0.90	0.031
	56	20.3	2.0	0.90	0.023
Great Falls (Vertical 20 TPH Hammermill)	28	12.7	2.4	0.81	0.056
	38	12.7	2.4	0.81	0.044
	48	12.7	2.4	0.81	0.033
	56	12.7	2.4	0.81	0.025

Figure 60 represents a convenient method for representation of test data gathered at different sites and serves to allow intelligent comparison of wear data that may have been collected from shredders where different types of solid waste and product sizes are experienced. The general conclusion that can be drawn from the data in the figure is that hard alloys yield significant reduction in hammer wear, for example, on the order of 60 percent if an alloy with a hardness of 56 R_c is used instead of an alloy with a hardness of 28 R_c. For an equivalent amount of material worn from the hammers, this 60 percent reduction in wear corresponds to a running time for hammers that are coated with the harder alloy that is 250 percent of that for hammers coated with the softer alloy.

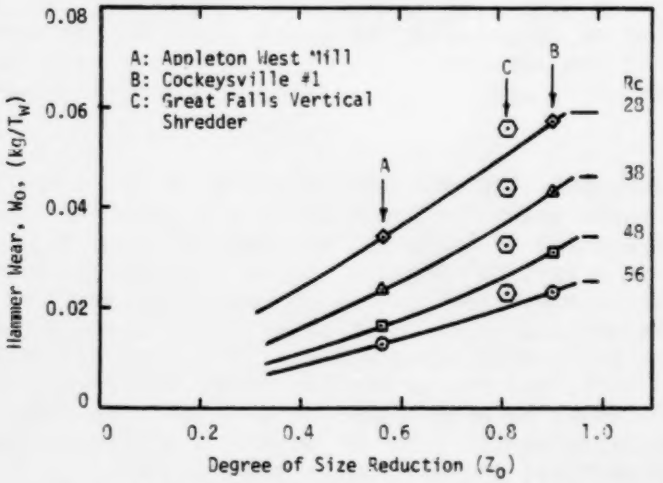


Figure 60. Hammer wear as a function of alloy hardness and degree of size reduction.

SITE SPECIFIC COMMENTS WITH REGARD TO HAMMER MAINTENANCE

Some general comments can be made about the present hammer maintenance procedures followed at each plant. Beginning first with the Appleton plant, consideration could be given to testing several hardfacing alloys in the range of 48 to 56 R_c (as deposited). Although Stoody 2134 (and therefore its wire equivalent Stoody 134) exhibited good wear characteristics, the harder Amsco Super 20 (56 R_c) exhibited 24 percent less wear than Stoody 2134 (0.013 kg/T versus 0.017 kg/T, respectively). For an equivalent amount of hammer material lost due to wear, Amsco Super 20 will wear approximately 31 percent longer than Stoody 2134. Any hardfacing alloys that exhibit as-deposited hardness values in the range of 48 to 56 R_c, as well as being compatible with manganese steel, would be satisfactory for testing purposes.

The McKay electrode that is used for hammer retipping at the Cockeysville facility provides good wear resistance. However, as noted for Appleton, possible improvements in wearing characteristics might be obtained if several harder alloys (e.g. 50 to 56 R_c) were tested. The estimated upper limit for reduction in hammer wear is approximately 25 percent.

SUMMARY OF SHREDDER PERFORMANCE

Based upon an evaluation which considers energy consumption and hammer wear as a consequence of shredding refuse to an equivalent particle size, no major differences could be discerned among the following shredders:

a. Allis Chalmers horizontal hammermill
b. Tracor-Marksman horizontal hammermill
c. American Pulverizer horizontal hammermill
d. Heil vertical hammermill

This observation follows mainly from analysis of the data depicted in Figures 44 and 60. First hand observation of each of these shredders in operation and undergoing maintenance provided no major discernible difference from an operational or maintenance point of view.

When compared to the four shredders listed previously, two shredders, namely the Newell horizontal hammermill and the Carborundum vertical shredder, exhibited low specific energy requirements (kwh/T) for shredding refuse to an equivalent product size. In the case of the Newell shredder, it is thought that the low energy requirements are derived mainly from the fact that only 14 hammers were utilized (as opposed to the 24 to 48 hammers used in the other horizontal hammermills that were tested) rather than from an inherently superior shredder design.

SECTION 7

COSTS ASSOCIATED WITH REFUSE SIZE REDUCTION

ENERGY COSTS FOR SHREDDING

Energy costs for size reduction can be estimated utilizing equation 15, which presents energy consumption (wet basis) as a function of nominal product size. If net specific energy is assumed to be 90 percent of the gross energy utilized (to account for freewheeling energy), equation 15 becomes

$$E_{o_w} \ (\mathrm{kwh}/T_w) = 39.50 \ X_{90}^{-0.81} \ (\mathrm{cm}) \tag{32}$$

If energy costs are estimated at $0.02/kwh, the cost of energy ($E) for size reduction can be estimated from

$$\$E \ (\$/T) = 0.79 \ X_{90}^{-0.81} \ (\mathrm{cm}) \tag{33}$$

The cost of energy versus nominal product size is shown in Figure 61. As shown in the figure, energy costs for primary shredding are in the range of $0.08 to $0.20 per ton. Energy costs rise steeply for nominal product sizes that are less than 3 cm, denoted as the "fine shred" region in the figure.

COMPARISON OF ALTERNATIVE HAMMER MAINTENANCE PROGRAMS

The hammer maintenance programs used at the six sites can be separated into two categories: hammer buildup and wear-and-scrap. The first method involves building up the hammers with buildup and/or hardfacing electrode after a given refuse tonnage has been shredded. In the second method, as the name implies, the hammers are worn until they no longer effectively shred refuse before being scrapped and replaced by new hammers.

By coincidence, of the six sites visited, three sites use the method of hammer buildup and three sites utilize the wear-and-scrap method. Conversations with the plant managers revealed some interesting information regarding the utility of each type of hammer maintenance program. Since each plant manager felt that the method used at his plant was the most cost effective, the issue should be put in its proper perspective.

In the following analysis, cost alone will be considered. Among those factors thus ignored are variations among sites with respect to operational procedures, availability of proper equipment for hammer changing and welding, proper training of maintenance personnel, and the fact that badly worn

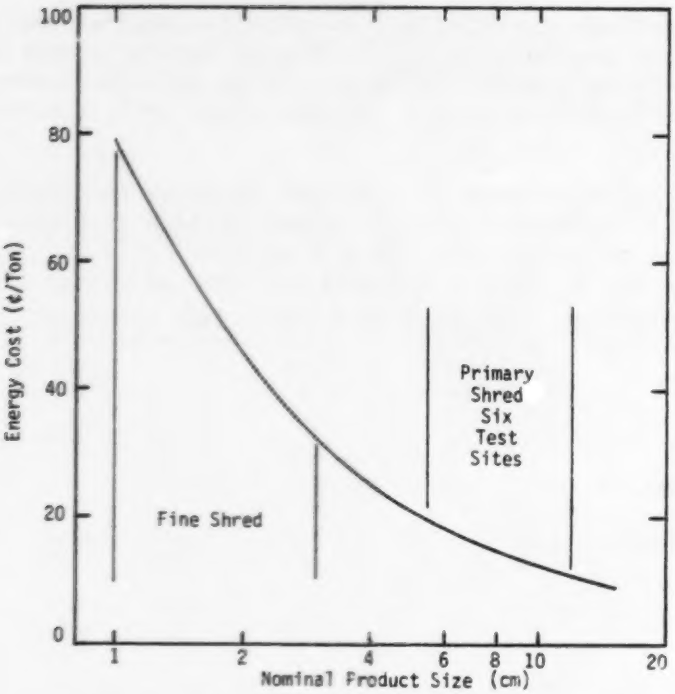


Figure 61. Cost of energy associated with size reduction.

hammers (which are inevitable in the wear-and-scrap method) affect particle size, energy requirements, and throughput. Neglect of such considerations does not mean that they are inconsequential, but rather that it is difficult to assign specific monetary values to them. Perhaps the two most effective means of minimizing the costs associated with either type of hammer maintenance program are proper training of maintenance personnel and availability of proper maintenance equipment.

Bearing in mind the preceding discussion and assuming a well-run hammer maintenance program, the two types of programs may be compared.

Three scenarios are examined based upon information provided by the plant managers and the experience of CRS. All three scenarios are developed assuming a horizontal hammermill with a nominal rating of 50 TPH and having a hammer complement of 24 hammers, each weighing 73 kg. All operational parameters (e.g. size of shredded product, input size and composition, rotor rpm, etc.) are assumed to be identical for all scenarios. Shred size is assumed to be approximately 90 percent passing 9 cm. In addition, each scenario assumes that both properly trained personnel and proper equipment are available. Proper equipment is considered to include mechanical or hydraulic pin pullers for pin removal and installation, overhead crane for hammer removal and installation, and a hydraulically actuated system for opening up the shredder.

These assumptions are necessary in order to compare programs for hammer maintenance under similar conditions. A site by site comparison was not used specifically because the different operational procedures used at each site significantly influence the time, and hence cost, required for hammer maintenance.

The cost breakdown for three different programs for hammer maintenance are summarized in Table 26. Case I assumes buildup of hammers once per week (every five days of operation). Case II assumes daily buildup of hammers during a second shift. Case III covers the wear-and-scrap alternative.

TABLE 26. TYPICAL COSTS FOR HAMMER MAINTENANCE

Cost Items	Man-Hours	$ Per Man-Hour	Total $	Tons	Unit Cost $ Per Ton	Annual Cost[g] $	Percent of Cost
CASE I: BUILDUP ONCE PER WEEK							
Labor							
remove and install	12	7	84	1,800[d]	0.047	4,900	11.9
welder[a]	40	11	440	1,800[d]	0.244	25,400	61.8
Materials							
hardfacing[f]			126	1,800[d]	0.070	7,300	17.8
hammers (2 sets)[b,c]			3,538	104,000[e]	0.034	3,500	8.5
TOTALS					0.395	41,100	100.0
CASE II: DAILY BUILDUP							
Labor							
welder[h]	9	13	117	400	0.292	30,400	73.6
Materials							
hardfacing[i]			35	400	0.088	9,100	22.0
hammers (1 set)[c,j]			1,769	104,000	0.017	1,800	4.4
TOTALS					0.397	41,300	100.0
CASE III: WEAR AND SCRAP							
Labor							
remove and install	12	7	84	7,200	0.012	1,200	2.6
Materials							
hammers (1 set)[k]			3,154	7,200	0.438	45,600	97.4
Salvage credit[l,m]			(235)	7,200	(0.033)	(3,400)	--
TOTALS					0.417	43,400	100.0

[a] Welder for re-tipping, regular time charge, 40 hours per set of 24 hammers

[b] one set = 24 hammers x 73 kg x $1.80/kg = $3,154; two sets needed, one for installation, one for retipping

[c] Amortized 2 years @ 8% per annum, capital recovery factor = 0.5608

[d] Tonnage per hammer change

[e] Annual tonnage: 50 TPH x 8 hr/day x 260 days/year

[f] 1800 T x 0.020 kg/T x $3.50/kg = $126

[g] Rounded dollars

[h] Welder for re-tipping, overtime charge, 9 hours to re-tip 24 hammers in place

[i] 50 TPD x 8 hr/day x 0.020 kg/T x $4.40/kg = $35

[j] one set = 24 hammers x 73 kg x $1.80/kg = 3,154; one set only, hammers welded in place

[k] one set = 24 hammers x 73 kg x $1.80/kg = $3,154; worn and scrapped

[l] Scrap value: $150 per metric ton = $0.15/kg

[m] Credit = (1,752 kg/set - (7,200 T x 0.026 kg/T))($0.15/kg) = $235 per set

Major items of cost are explained in the footnotes listed in Table 26. Some of the significant assumptions used in developing the costs include:

1. Hammer wear of 0.020 kg/T_W and 0.026 kg/T_W for hardfaced hammers utilized in Cases I and II and bare hammers utilized in Case III, respectively. As indicated previously, wear for bare hammers is greater than wear for properly hardfaced hammers.

2. Labor costs for maintenance personnel and welders are best estimates based upon current maintenance practice and CRS experience.

3. Hammer life for Case III (wear-and-scrap) is 7,200 tons, which corresponds to wearing away approximately 10 percent of each hammer.

4. Hammer life for Cases I and II is estimated to be two years. Despite buildup and hardfacing, hammers eventually wear out (e.g. hammer thickness decreases, pin holes elongate, etc.). Two years of life for hammers may be a liberal estimate.

5. Two sets of hammers are required for Case I, one set is built up while the other is run in the shredder.

6. Only one set of hammers is required for Case II since these hammers are rebuilt during a second shift.

7. The credit for scrapped hammers in Case III is assumed to be $150/T.

The unit cost ($/T shredded) and the annual cost for hammer maintenance for all the cases are summarized in Table 27. Under the assumptions for these cases, the unit costs and annual costs are identical for all practical purposes. The unit cost is found to be in each case approximately $0.40/T, while the annual cost is approximately $42,000 based upon 104,000 TPY. The unit cost of $0.40/T is in the range of $0.25 to $0.75 per ton often quoted by shredder manufacturers for hammer maintenance allowance.

TABLE 27. COST SUMMARY FOR HAMMER MAINTENANCE PROGRAMS

CASE	DESCRIPTION	1978 UNIT COST ($/Ton)	ANNUAL COST (1978 $)
I	Build-up once per week	0.395	41,100
II	Daily build-up	0.397	41,300
III	Wear-and-scrap	0.417	43,400

In Cases I and II the majority of the cost is a result of the actual buildup and/or hardfacing operation (refer to "Percent of Cost" column in Table 26). In Case III practically all of the total cost is a consequence of purchasing replacement hammers.

The similarity in cost for the three alternative programs for hammer maintenance may explain the fact that the opinions of the plant managers were split evenly on the buildup versus wear-and-scrap question. Since buildup and wear-and-scrap alternatives are practically identical from the standpoint of cost, the buildup alternative should be the preferred method for hammer maintenance. The rationale for this judgment stems from the fact that particle size, throughput capacity, and energy consumption will remain relatively constant and predictable if a regular schedule for rebuilding hammers is followed.

SUMMARY OF COSTS

Based upon previously developed costs for actual size reduction of refuse and hammer maintenance, energy and hammer maintenance costs can be compared for the case of a nominal product size of 9 cm, which is characteristic of primary shredding. The energy cost for size reduction for such a case would be approximately $0.19/T, while hammer maintenance costs would run approximately $0.40/T. Consequently, hammer maintenance cost is approximately twice the cost of the energy required for size reduction, based upon production of a nominal product size of 9 cm.

REFERENCES

1. Shiflett, G. R. A Model for the Swing Hammermill Size Reduction of Residential Refuse. Ph.D. Thesis, University of California at Berkeley, Berkeley, California, 1978.

2. Trezek, G. J. and Savage, G. M. Size Reduction in Solid Waste Management. EPA-600/2-77-131, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

3. Trezek, G. J. and Savage, G.M. Size Reduction in Solid Waste Processing, Progress Report 1973-1976. U.S. Environmental Protection Agency, Cincinnati, Ohio.

APPENDIX

The following summaries of data present test data from each shredder in tabular form. The summaries are arranged by site, and tabulated data within sites is organized by each shredder that was evaluated.

Shredder Performance Data Summary

Site: Appleton - East mill
Date: October 2-10, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	18.3	13.7	24.9	134.5	200.0	47.0	153.0	8.4	11.2	2.2	8.7
2	33.4	17.5	47.5	-	100.0	47.0	53.0	1.6	3.0	3.6	8.9
3	29.2	-	-	-	187.5	47.0	140.5	4.8	-	-	-
4	39.8	23.5	40.9	39.5	214.3	47.0	167.3	4.2	7.1	5.5	12.0
5	15.4	12.7	17.4	43.3	90.9	47.0	43.9	2.9	3.5	3.1	10.1
6	47.5	34.0	28.4	57.4	125.0	47.0	78.0	1.6	2.3	3.4	10.5
7	39.1	22.2	43.1	52.7	125.0	47.0	78.0	2.0	3.5	3.5	9.7
8	30.4	18.0	40.9	49.3	117.6	47.0	70.6	2.3	3.9	4.5	9.7
9	3.5	2.1	41.1	6.4	54.8	47.0	7.8	2.2	3.7	5.5	10.5
10	18.0	12.1	32.7	51.4	100.0	47.0	53.0	2.9	4.4	3.9	9.8
11	24.5	15.0	38.8	69.9	102.6	47.0	55.6	2.3	3.7	3.2	8.6

Shredder Performance Data Summary

Site: Appleton - East mill
Date: October 2-10. 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	50.6	-	-	-	-	-
2	-	-	-	-	-	42.8	-	-	-	-	-
3	-	-	-	-	-	47.6	-	-	-	-	-
Avg	-	-	-	-	-	47.0	-	-	-	-	-

Shredder Performance Data Summary

Site: Appleton - West mill
Date: October 2-10, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	13.9	9.9	28.5	49.9	80.0	41.0	39.0	2.8	3.9	6.4	12.8
2	30.1	16.5	45.1	81.2	105.3	41.0	64.3	2.1	3.9	4.4	10.2
3	10.5	8.7	16.7	16.1	111.1	41.0	70.1	6.7	8.1	6.1	10.5

Shredder Performance Data Summary

Site: Appleton - West mill
Date: October 2-10, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	41.7	-	-	-	-	-
2	-	-	-	-	-	38.5	-	-	-	-	-
3	-	-	-	-	-	42.8	-	-	-	-	-
Avg	-	-	-	-	-	41.0	-	-	-	-	-

Shredder Performance Data Summary

Site: Ames - Primary

Date: November 25 - December 6, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	18.7	15.2	18.5	-	266.7	53.2	213.5	11.4	14.0	3.81	9.65
2	15.9	13.8	13.2	-	156.9	53.2	103.7	6.5	7.5	4.70	14.22
3	25.0	21.4	14.5	-	166.7	53.2	113.5	4.5	5.3	5.08	8.89
4	17.7	13.4	24.1	-	96.6	53.2	43.4	2.5	3.2	6.35	11.94
5	35.1	28.6	18.4	-	261.4	53.2	208.2	5.9	7.3	4.70	10.92
6	10.6	8.3	22.0	-	111.1	53.2	57.9	5.5	7.0	5.08	10.67
7	21.2	17.4	17.9	-	125.8	53.2	72.6	3.4	4.2	3.68	21.08
8	13.5	12.0	11.4	-	130.7	53.2	77.5	5.7	6.5	6.60	10.67
9	10.6	9.9	6.9	-	98.0	53.2	44.8	4.2	4.5	5.33	10.67
10*	27.9	24.6	12.0	-	95.2	53.2	42.0	1.5	1.7	0.86	8.64

*Test #10 was mainly dirt, etc. and was judged as unreliable data.

Shredder Performance Data Summary

Site: Ames - Primary
Date: November 25 - December 6, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	56.8	-	-	-	-	-
2	-	-	-	-	-	51.1	-	-	-	-	-
3	-	-	-	-	-	52.4	-	-	-	-	-
4	-	-	-	-	-	57.4	-	-	-	-	-
5	-	-	-	-	-	50.7	-	-	-	-	-
6	-	-	-	-	-	50.6	-	-	-	-	-
Avg	-	-	-	-	-	53.2	-	-	-	-	-

Shredder Performance Data Summary

Site: Ames - Secondary

Date: November 25 - December 6, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	24.8	18.7	24.4	-	350.9	40.5	310.4	12.5	16.6	1.27	3.05
2	26.9	21.1	21.4	-	392.2	40.5	351.7	13.1	16.7	1.55	4.52
3	22.4	14.1	37.0	-	416.7	40.5	376.2	16.8	26.7	0.97	3.20
4	20.3	16.5	18.7	-	246.9	40.5	206.4	10.2	12.5	1.35	3.05
5	7.0	5.7	18.5	-	56.0	40.5	15.5	2.2	2.7	1.65	4.52
6	22.2	17.6	20.8	-	256.4	40.5	215.9	9.7	12.3	1.57	3.43
7	15.8	12.8	19.2	-	256.4	40.5	215.9	13.7	16.9	1.52	3.43
8	17.9	13.6	24.1	-	185.2	40.5	144.7	8.1	10.6	1.12	2.97
9	24.2	20.3	16.1	-	202.0	40.5	161.5	6.7	8.0	1.30	3.10
10	27.2	22.2	18.2	-	215.1	40.5	174.6	6.4	7.9	1.24	3.12

Shredder Performance Data Summary

Site: Ames - Secondary

Date: November 25 - December 6, 1977

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	34.2	-	-	-	-	-
2	-	-	-	-	-	46.7	-	-	-	-	-
3	-	-	-	-	-	43.2	-	-	-	-	-
4	-	-	-	-	-	42.5	-	-	-	-	-
5	-	-	-	-	-	32.8	-	-	-	-	-
6	-	-	-	-	-	43.5	-	-	-	-	-
Avg	-	-	-	-	-	40.5	-	-	-	-	-

Shredder Performance Data Summary

Site: Teledyne #1 (F = forward, R = reverse)
Date: February 18-24, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1-F	22.6	18.8	16.8	-	277.8	64.3	213.5	9.4	11.4	2.3	7.8
2-F	41.1	35.4	13.9	-	625.0	64.3	560.7	13.6	15.8	1.9	6.3
3-F	45.4	35.3	22.2	-	416.7	64.3	352.4	7.8	10.0	2.3	6.1
4-F	48.0	41.8	13.0	-	625.0	64.3	560.7	11.7	13.4	3.1	8.3
5-F	26.4	22.4	15.2	-	434.8	64.3	370.5	14.0	16.5	2.0	4.9
6-F	52.3	43.7	16.4	-	512.8	64.3	448.5	8.6	10.3	1.5	4.9
7-R	63.2	53.0	16.1	-	666.7	67.8	598.9	9.5	11.3	1.6	4.3
8-R	41.1	35.2	14.4	-	476.2	67.8	408.4	9.9	11.6	1.6	5.3
9-R	56.5	48.2	14.7	-	714.3	67.8	646.5	11.4	13.4	2.2	6.4
10-R	62.8	40.7	35.2	-	416.7	67.8	348.9	5.6	8.6	2.3	7.4
11-R	39.4	34.6	12.3	-	384.6	67.8	316.8	8.0	9.2	2.3	7.0
12-R	95.7	81.9	14.4	-	1025.6	67.8	957.8	10.0	11.7	2.1	6.2
13-F	51.5	-	-	-	701.8	64.3	637.5	12.4	-	-	-
14-F	53.3	-	-	-	952.4	64.3	888.1	16.7	-	-	-
15-F	56.6	-	-	-	952.4	64.3	888.1	15.7	-	-	-
16-F	82.1	-	-	-	833.3	64.3	769.0	9.4	-	-	-

Shredder Performance Data Summary

Site: Teledyne #1 Forward
Date: February 18-24, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	65.1	-	-	-	-	-
2	-	-	-	-	-	64.6	-	-	-	-	-
3	-	-	-	-	-	64.6	-	-	-	-	-
4	-	-	-	-	-	65.9	-	-	-	-	-
5	-	-	-	-	-	63.1	-	-	-	-	-
6	-	-	-	-	-	62.2	-	-	-	-	-
Avg	-	-	-	-	-	64.3	-	-	-	-	-

Shredder Performance Data Summary

Site: Teledyne #1 Reverse
Date: February 18-24, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	69.4	-	-	-	-	-
2	-	-	-	-	-	69.4	-	-	-	-	-
3	-	-	-	-	-	68.3	-	-	-	-	-
4	-	-	-	-	-	64.1	-	-	-	-	-
Avg	-	-	-	-	-	67.8	-	-	-	-	-

Shredder Performance Data Summary

Site: Great Falls 20 TPH Vertical Hammermill

Date: October 7-13, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	12.3	10.8	12.4	-	120	21.7	98.3	7.6	9.1	0.9	3.2
2	17.1	14.7	14.4	-	120	21.7	98.3	5.7	6.7	1.4	6.3
3	19.4	13.4	29.2	-	114.3	21.7	92.6	4.8	6.9	1.5	9.3
4	10.0	8.1	18.9	-	120	21.7	98.3	9.9	12.1	3.0	5.1
5	16.5	10.8	34.5	-	120	21.7	98.3	6.0	9.1	2.3	4.1
6	11.9	10.1	15.8	-	100	21.7	78.3	6.6	7.8	3.4	6.7
7	13.9	11.2	19.7	-	100	21.7	78.3	5.6	7.0	2.3	4.1
8	16.0	11.1	30.7	-	100	21.7	78.3	4.9	7.1	3.6	7.5
9	13.3	10.7	19.2	-	120	21.7	98.3	7.4	9.2	2.5	5.2
10	19.0	15.3	19.5	-	150	21.7	128.3	6.7	8.4	2.7	5.4
11	14.3	10.7	24.8	-	150	21.7	128.3	9.0	12.0	2.2	4.9
12	13.3	11.4	14.2	-	54.5	21.7	32.8	2.5	2.9	2.4	5.6

Shredder Performance Data Summary

Site: Great Falls 20 TPH Vertical Hammermill
Date: October 7-14, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	23.1	-	-	-	-	-
2	-	-	-	-	-	21.3	-	-	-	-	-
3	-	-	-	-	-	21.3	-	-	-	-	-
4	-	-	-	-	-	21.2	-	-	-	-	-
Ave.	-	-	-	-	-	21.7	-	-	-	-	-

Shredder Performance Data Summary

Site: Tinton Falls Vertical Ring Shredder #2
Date: October 21-27, 1978

Test	$\dot{m}_w$ ($T_w PH$)	$\dot{m}_d$ ($T_d PH$)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	83.0	-	-	-	240.0	38.5	201.5	2.4		-	-
2	34.9	-	-	-	120.0	38.5	81.5	2.3		-	-
3	91.9	-	-	-	240.0	38.5	201.5	2.2		-	
4	34.3	-	-	-	120.0	38.5	81.5	2.4		-	-
5	76.6		20.5	-	218.2	38.5	179.7	2.4		3.7	10.1
6	62.7		17.8	-	171.4	38.5	132.9	2.1		4.6	13.7
7	61.5		25.4	-	133.3	38.5	94.8	1.5		3.7	10.7
8	36.1		19.8	-	109.1	38.5	70.6	2.0		3.5	8.9
9	82.3		20.9	-	171.4	38.5	132.4	1.6		4.4	10.4
10	78.3		21.0	-	320.0	38.5	281.5	3.6		2.4	6.9
11	99.5		23.1	-	200.0	38.5	161.5	1.6		2.9	7.0
12	70.4		17.2	-	240.0	38.5	201.5	2.9		3.1	8.6
13	67.7		22.0	-	171.4	38.5	132.9	2.0		3.5	9.4
14	37.1		17.4	-	126.3	38.5	87.8	2.4		4.1	9.3
15	20.7		16.9	-	100.0	38.5	61.5	3.0		5.0	10.3
16	36.6		7.9	-	120.0	38.5	81.5	2.2		4.8	10.4

Shredder Performance Data Summary

Site: Tinton Falls Vertical Ring Shredder #2
Date: October 21-27, 1978

Test	$\dot{m}_w$ ($T_w PH$)	$\dot{m}_d$ ($T_d PH$)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	40.0	-	-	-	-	-
2	-	-	-	-	-	36.8	-	-	-	-	-
3	-	-	-	-	-	38.7	-	-	-	-	-
Ave.	-	-	-	-	-	38.5	-	-	-	-	-

Shredder Performance Data Summary

Site: Odessa
Date: November 25-December 2, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	127.4	99.6	22.0	-	227.7	101.7	126.0	1.0	1.3	1.2	5.0
2	83.2	65.1	21.7	-	263.7	101.7	162.0	1.9	2.5	2.8	6.9
3	67.6	53.1	21.4	-	182.7	101.7	81.0	1.2	1.5	3.9	9.9
4	76.1	59.2	22.2	-	250.2	101.7	148.5	2.0	2.5	2.5	6.2
5	81.9	67.6	17.4	-	264.6	101.7	162.9	2.0	2.4	2.9	8.0
6	124.5	108.3	13.0	-	147.6	101.7	45.9	0.4	0.4	2.5	20.0
7	13.3	11.9	10.7	-	106.2	101.7	4.5	0.3	0.4	5.5	12.4
8	96.9	74.8	22.8	-	178.2	101.7	76.5	0.8	1.0	2.2	6.9
9	98.2	79.3	19.2	-	170.1	101.7	68.4	0.7	0.9	3.6	9.2
10	68.3	57.9	15.3	-	162.9	101.7	61.2	0.9	1.1	4.5	10.2
11	89.1	70.7	20.7	-	297.0	101.7	195.3	2.2	2.8	2.4	6.7
12	57.9	53.6	7.5	-	108.9	101.7	7.2	0.1	0.1	4.5	9.2

Shredder Performance Data Summary

Site: Odessa

Date: November 25- December 2, 1978

Test	$\dot{m}_w$ (T_wPH)	$\dot{m}_d$ (T_dPH)	MC (%)	H (kg)	P_G (Kw)	P_{FW} (Kw)	P_N (Kw)	E_{o_w} (Kwh/T_w)	E_o (Kwh/T_d)	X_o (cm)	X_{90} (cm)
1	-	-	-	-	-	97.4	-	-	-	-	-
2	-	-	-	-	-	99.3	-	-	-	-	-
3	-	-	-	-	-	99.3	-	-	-	-	-
4	-	-	-	-	-	98.7	-	-	-	-	-
5	-	-	-	-	-	104.9	-	-	-	-	-
6	-	-	-	-	-	103.3	-	-	-	-	-
7	-	-	-	-	-	108.7	-	-	-	-	-
Ave.	-	-	-	-	-	101.7	-	-	-	-	-